

# Bulking II: Classifications of Cellular Automata<sup>☆</sup>

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## Abstract

This paper is the second part of a series of two papers dealing with bulking: a way to define quasi-order on cellular automata by comparing space-time diagrams up to rescaling. In the present paper, we introduce three notions of simulation between cellular automata and study the quasi-order structures induced by these simulation relations on the whole set of cellular automata. Various aspects of these quasi-orders are considered (induced equivalence relations, maximum elements, induced orders, etc) providing several formal tools allowing to classify cellular automata.

*Key words:* cellular automata, bulking, grouping, classification

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## 1. Introduction

In the first paper [8], we have developped a general theory of bulking aimed at defining quasi-orders on cellular automata based on the idea of space-time rescaling. The present paper focuses on three instances of such quasi-orders and uses them as classification tools over the set of one-dimensional cellular automata.

Classifying does not make sense without additional assumptions (some criteria of classification). If in Wolframs papers [39] these criteria were implicit and informal, several classifications with explicit and formal criteria have been since proposed [10, 4, 19]. Usually, the criteria are those of dynamical systems and consist in a finite list of qualitative behaviors. Our approach here is different: we don't define any *a priori* list of behaviors. Instead, we consider a simulation relation (a quasi-order) which tells when some cellular automaton is able to reproduce the behavior of another. The criterion of classification is then the definition of the quasi-order. Our central thesis is that, when it comes to apprehend the great variety of behaviors in cellular automata, the language of orders (equivalence classes, chains, ideals, maximal elements, distance to the bottom, etc) is more adapted than a finite list of monadic predicates (of the form "having property P" for some P).

In this paper, we introduce three quasi-orders. They are all defined according to the same scheme developped in the companion paper [8]: some local

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<sup>☆</sup>The results presented here first appeared to a great extent in French in the PhD theses of Ollinger [29] and Theyssier [36]

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comparison relation up to spatio-temporal rescaling. They only differ in the local comparison they use, which are based on the two following basic notions:

- the *injection* of a small system ( $A$ ) *into* a larger one ( $B$ ),
- the *projection* of a large system ( $B$ ) *onto* a smaller one ( $A$ ).

The three quasi-orders can be defined informally as follows:

- an *injective* simulation of  $A$  by  $B$ , denoted by  $A \preceq_i B$ , is an injection of some rescaling of  $A$  into some rescaling of  $B$ ;
- a *surjective* simulation of  $A$  by  $B$ , denoted by  $A \preceq_s B$ , is the projection of some rescaling of  $B$  onto some rescaling of  $A$ ;
- a *mixed* simulation of  $A$  by  $B$ , denoted by  $A \preceq_m B$ , is the injection into some rescaling of  $B$  of some  $C$  that projects onto some rescaling of  $A$ .

In the context of cellular automata, the two notions of local comparison above (injection and projection) translate into the following. The first notion is the *subautomaton* relation ( $B$  obtained from  $A$  by forgetting some states) and the second one is the *quotient* relation ( $B$  obtained from  $A$  by identifying some states).

The subautomaton relation was already introduced in [8] and its importance in cellular automata is illustrated by theorems 4 and 5 of that paper.

The quotient relation can be seen as a particular case of the notion of factor in dynamical systems theory and symbolic dynamics (homomorphism between shift-commuting continuous global maps, see [21]). More intuitively, the quotient relation is a means to extract coarse-grained information ( $A$ ) from a complex system ( $B$ ) (see [17]). For instance, the metaphor of particles moving in a stable background used in the literature of cellular automata [3] follows this idea: some information (e.g. the phase of the background) is hidden by identification of states. However, our definition of quotient requires that both  $B$  (the original system) and  $A$  (the one obtained after identification of some states) are cellular automata.

We study these orders with several points of view and aim at understanding their structure as well as showing that they suitably capture many classical properties or phenomena of cellular automata.

For instance, concerning the phenomenon of universality, we show that orders  $\preceq_i$  and  $\preceq_m$  have a maximum, that classes of CA having Turing-universality can be obtained by simulating (in a way closed to Smith III [33]) a universal Turing machine, and that such a class is not necessarily at the top of the order.

As another example, we show that many global properties of cellular automata as dynamical systems (reversibility, sensitivity, expansivity, etc) or cellular automata as computational devices (ability to simulate a Turing head, or to propagate some signal) characterize an ideal or a filter in our orders.

*Overview of the paper.* Section 1.1 introduces three different comparison relations which are three different instances of the bulking theory developed in the companion paper [8]. Section 2 sets the definitions of these three notions of simulations and establishes some of their basic properties. Section 3 studies the 'bottom' of each of the three quasi-orders induced on CA, *i.e.* CA or classes of

CA of least complexity. Section 4 focuses on the order structure with respect to various classical properties of CA, and from a computability point of view. Then section 5 explores the set of CA at the 'top' of these quasi-orders: universal CA. Once again, the point of view is both structural and computational. Finally, section 6 is devoted to the construction of noticeable induced orders (like infinite chains), and the study of how simple families of CA spread over these quasi-orders.

### 1.1. Definitions

In this paper, we adopt the setting of one-dimensional cellular automata with a canonical neighborhood (connected and centered). A cellular automaton (CA) is a triple  $\mathcal{A} = (S, r, f)$  where:

- $S$  is the (finite) *state set*,
- $r$  is the neighborhood *radius*,
- $f : S^{2r+1} \rightarrow S$  is the *local transition function*.

A coloring of the lattice  $\mathbb{Z}$  with states from  $S$  (*i.e.* an element of  $S^{\mathbb{Z}}$ ) is called a *configuration*. To  $\mathcal{A}$  we associate a global function  $G$  acting on configurations by synchronous and uniform application of the local transition function. Formally,  $G : S^{\mathbb{Z}} \rightarrow S^{\mathbb{Z}}$  is defined by:

$$G(x)_z = f(x_{z-r}, \dots, x_{z+r})$$

for all  $z \in \mathbb{Z}$ . Several CA can share the same global function although there are syntactically different (different radii and local functions). However we are mainly interested in global functions and will sometimes define CA through their global function without specifying particular syntactical representations. In addition, the Curtis-Heldund-Lyndon theorem [13] allows us to freely compose global CA functions to construct new CA without manipulating explicitly the underlying syntactical representation.

When dealing with several CA simultaneously, we use index notation to denote their respective state sets, radii and local functions. For instance, to  $\mathcal{A}$  we associate  $S_{\mathcal{A}}$ ,  $r_{\mathcal{A}}$  and  $f_{\mathcal{A}}$ .

This paper will make an intensive use of **PCS** transforms defined in section 4.2 of [8], but restricted to dimension 1. With this restriction, a **PCS** transform  $\alpha$  has the form  $\alpha = \langle m, \tau, T, s \rangle$  where  $m$  and  $T$  are positive integers,  $s$  is a (possibly negative) integer and  $\tau$  is either 1 or  $-1$ .

For any CA  $\mathcal{A}$ , we denote by  $\mathcal{A}^{(\alpha)}$  or more explicitly  $\mathcal{A}^{\langle m, \tau, T, s \rangle}$  the application of  $\alpha$  to  $\mathcal{A}$ , which is, according to notations of [8], a CA of state set  $S_{\mathcal{A}}^m$  and global rule:

$$\langle \boxplus_m, V_{\tau} \odot \square_m \rangle \circ \sigma_s \circ G_{\mathcal{A}}^T \circ \langle \boxplus_m, V_{\tau} \odot \square_m \rangle^{-1}.$$

To simplify notation we will use a shortcut for purely temporal transforms: for any CA  $\mathcal{A}$  we denote by  $\mathcal{A}^t$  the CA  $\mathcal{A}^{\langle 1, 1, t, 0 \rangle}$ . Finally, as another special case, we denote by  $\mathcal{A}^{[n]}$  the grouped instance of  $\mathcal{A}$  of parameter  $n$ : it corresponds to the transform  $\langle n, 1, n, 0 \rangle$  (see [8] for a detailed exposition of grouping).

## 2. Canonical orders

In this section we introduce the three bulking quasi-orders that are studied all along the paper. They are obtained by applying the bulking axiomatics developed in the companion paper [8] to three 'canonical' relations between local rules of CA.

Those three 'canonical' relations are in turn based on two classical notions of morphism between local transition rules of CA: sub-automaton and quotient-automaton. As shown below, the three relations we consider are exactly the reflexive and transitive relations that can be defined by compositions of one or more such morphisms.

### 2.1. From Three Local Relations to Three Bulking Quasi-Orders

A *sub-automaton* is a restriction of a CA to a stable sub-alphabet. A *quotient* is a projection of a CA onto a smaller alphabet and compatible with the local transition rule<sup>1</sup>. Both define a kind of morphism between cellular automata:

- $\mathcal{A}$  is a *sub-automaton* of  $\mathcal{B}$ , denoted  $\mathcal{A} \sqsubseteq \mathcal{B}$ , if there is an injective map  $\iota : S_{\mathcal{A}} \rightarrow S_{\mathcal{B}}$  such that  $\bar{\iota} \circ G_{\mathcal{A}} = G_{\mathcal{B}} \circ \bar{\iota}$ , where  $\bar{\iota} : S_{\mathcal{A}}^{\mathbb{Z}} \rightarrow S_{\mathcal{B}}^{\mathbb{Z}}$  denotes the uniform extension of  $\iota$ . We often write  $\mathcal{A} \sqsubseteq_{\iota} \mathcal{B}$  to make the map  $\iota$  explicit.
- $\mathcal{A}$  is a *quotient* of  $\mathcal{B}$ , denoted  $\mathcal{A} \trianglelefteq \mathcal{B}$ , if there is a surjective (onto) map  $s$  from  $S_{\mathcal{B}}$  to  $S_{\mathcal{A}}$  such that  $\bar{s} \circ G_{\mathcal{B}} = G_{\mathcal{A}} \circ \bar{s}$ , where  $\bar{s} : S_{\mathcal{B}}^{\mathbb{Z}} \rightarrow S_{\mathcal{A}}^{\mathbb{Z}}$  denotes the uniform extension of  $s$ . We also write  $\mathcal{A} \trianglelefteq_s \mathcal{B}$  to make the map  $s$  explicit.

Relations  $\sqsubseteq$  and  $\trianglelefteq$  are quasi-orders (reflexive and transitive) and it is straightforward to check that their induced equivalence relation is the relation of isomorphism between cellular automata (equality up to state renaming) denoted by  $\equiv$ .

It is also straightforward to check that  $\sqsubseteq$  and  $\trianglelefteq$  are incomparable (none of them is implied by the other one). It is thus interesting to consider compositions of them. The composition of two relations  $R_1$  and  $R_2$  is the relation  $R_1 \cdot R_2$  defined by

$$R_1 \cdot R_2 = \{(x, y) : \exists z, (x, z) \in R_1 \text{ and } (z, y) \in R_2\}.$$

We denote by  $\mathcal{R}$  the set of relations obtained by (finite) composition of  $\trianglelefteq$  and  $\sqsubseteq$ . Any relation of  $\mathcal{R}$  is a priori interesting, but the following theorem justifies that we restrict to  $\trianglelefteq$ ,  $\sqsubseteq$  and the composition  $\trianglelefteq \cdot \sqsubseteq$  only. In the sequel  $\trianglelefteq \cdot \sqsubseteq$  is denoted by  $\trianglelefteq \sqsubseteq$  and, as for  $\sqsubseteq$  and  $\trianglelefteq$ , we use the infix notation  $(\mathcal{A} \trianglelefteq \sqsubseteq \mathcal{B})$ .

#### Theorem 2.1.

1. any relation  $R \in \mathcal{R}$  is included in  $\trianglelefteq \sqsubseteq$  (i.e.,  $(\mathcal{A}, \mathcal{B}) \in R$  implies  $\mathcal{A} \trianglelefteq \sqsubseteq \mathcal{B}$ ) ;
2. the transitive relations of  $\mathcal{R}$  are exactly:  $\trianglelefteq$ ,  $\sqsubseteq$  and  $\trianglelefteq \sqsubseteq$ .

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<sup>1</sup>A quotient is a particular kind of *factor*, a classical notion in dynamical systems theory and symbolic dynamics [20]

PROOF. We first prove that if  $\mathcal{A} \sqsubseteq \cdot \preceq \mathcal{B}$  then  $\mathcal{A} \leq \mathcal{B}$ , which is sufficient to prove assertion 1 by transitivity of  $\sqsubseteq$  and of  $\preceq$ . So consider  $\mathcal{A}$ ,  $\mathcal{B}$  and  $\mathcal{C}$  such that  $\mathcal{A} \sqsubseteq_{\iota} \mathcal{C}$  and  $\mathcal{C} \preceq_s \mathcal{B}$ . Then consider  $Q = s^{-1} \circ \iota(S_{\mathcal{A}})$ . We have  $G_{\mathcal{B}}(Q^{\mathbb{Z}}) \subseteq Q^{\mathbb{Z}}$  because

$$\begin{aligned} \bar{s} \circ G_{\mathcal{B}}(Q^{\mathbb{Z}}) &= G_{\mathcal{C}} \circ \bar{s}(Q^{\mathbb{Z}}) \text{ (because } \mathcal{C} \preceq_s \mathcal{B}) \\ &= G_{\mathcal{C}} \circ \bar{\tau}(S_{\mathcal{A}}^{\mathbb{Z}}) \text{ (by definition of } Q) \\ &= \bar{\tau} \circ G_{\mathcal{A}}(S_{\mathcal{A}}^{\mathbb{Z}}) \text{ (because } \mathcal{A} \sqsubseteq_{\iota} \mathcal{C}) \\ &\subseteq \bar{\tau}(S_{\mathcal{A}}^{\mathbb{Z}}). \end{aligned}$$

The CA  $\mathcal{X} = (Q, r_{\mathcal{B}}, f_{\mathcal{B}})$  is thus well-defined and by definition we have  $\mathcal{X} \sqsubseteq \mathcal{B}$ . Moreover, we have  $\mathcal{A} \preceq_{\iota^{-1} \circ s} \mathcal{X}$  because  $\iota^{-1} \circ s : Q \rightarrow A$  is well-defined and onto, and because

$$\overline{\iota^{-1} \circ s} \circ G_{\mathcal{X}} = G_{\mathcal{A}} \circ \overline{\iota^{-1} \circ s}$$

since  $\bar{s} \circ G_{\mathcal{B}} = G_{\mathcal{C}} \circ \bar{s}$  and  $\overline{\iota^{-1} \circ s} \circ G_{\mathcal{C}} = G_{\mathcal{A}} \circ \overline{\iota^{-1} \circ s}$  over  $(\iota(A))^{\mathbb{Z}} = \bar{s}(Q^{\mathbb{Z}})$ . Hence  $\mathcal{A} \leq \mathcal{B}$  and assertion 1 is proven.

Given assertion 1 we have  $\mathcal{R} = \{\preceq, \sqsubseteq, \sqsubseteq \cdot \preceq, \leq\}$ . To prove assertion 2, it is thus sufficient to prove that  $\sqsubseteq \cdot \preceq$  is not transitive. To do this, consider  $S_{\mathcal{A}} = \{0, \dots, p-1\}$  with  $p$  prime,  $p \geq 5$ , and let  $\alpha, a_0, a_1, b_0, b_1$  be five distinct elements of  $S_{\mathcal{A}}$ . Then consider  $\mathcal{A}$ , the CA with state set  $S_{\mathcal{A}}$ , radius 1 and local rule  $f_{\mathcal{A}}$  defined by:

$$f_{\mathcal{A}}(*, x, y) = \begin{cases} a_{1-i} & \text{if } x \neq \alpha \text{ and } y = a_i, \\ b_{1-i} & \text{if } x \neq \alpha \text{ and } y = b_i, \\ y + 1 \bmod p & \text{else.} \end{cases}$$

$f_{\mathcal{A}}$  depends only on two variables. Suppose now that there is some AC  $\mathcal{B}$  with at least two states such that  $\mathcal{B} \preceq_{\pi} \mathcal{A}$ . We will show that  $\pi$  must be one-to-one. Suppose for the sake of contradiction that there are distinct elements  $x$  and  $y$  in  $S_{\mathcal{A}}$  such that  $\pi(x) = \pi(y)$ . Then, because  $f_{\mathcal{A}}(*, \alpha, z) = z + 1 \bmod p$  for any  $z$ , we have  $\pi(x + 1 \bmod p) = \pi(y + 1 \bmod p)$  and more generally

$$\pi(x + i \bmod p) = \pi(y + i \bmod p)$$

for all  $i \in \mathbb{N}$ . So, supposing without loss of generality  $y > x$ , let  $k = y - x$ . We deduce from above that  $\pi(y) = \pi(y + jk \bmod p)$  for all  $j \in \mathbb{N}$  and, by elementary group theory, that  $\pi$  is constant equal to  $\pi(y)$  (because  $p$  is prime and  $k \neq 0$ ). This is in contradiction with the fact that  $\pi$  has image  $S_{\mathcal{B}}$  which has at least two elements. So  $\pi$  is one-to-one and  $\mathcal{B}$  is isomorphic to  $\mathcal{A}$ . Now consider  $\mathcal{C}$ , the identity CA over state set  $S_{\mathcal{C}} = \{0, 1\}$ . Since  $\mathcal{C}$  possesses 2 quiescent states and  $\mathcal{A}$  has no quiescent state (straightforward from the definition of  $f_{\mathcal{A}}$  above), we have  $\mathcal{C} \not\sqsubseteq \mathcal{A}$ . With the discussion above, we can conclude that  $\mathcal{C} \not\sqsubseteq \mathcal{A}$ .

However, we have  $\mathcal{B} \leq \mathcal{A}$  because the states  $\{a_0, a_1, b_0, b_1\}$  induce a sub-automaton  $\mathcal{C}$  of  $\mathcal{A}$  which verifies  $\mathcal{B} \preceq_s \mathcal{C}$  where  $s : \{a_0, a_1, b_0, b_1\} \rightarrow \{0, 1\}$  is defined by  $s(a_i) = 0$  et  $s(b_i) = 1$ . Assertion 2 follows since the relation  $\leq$  is included in the composition of the relation  $\sqsubseteq \cdot \preceq$  with itself. ■

Like  $\sqsubseteq$  (already considered in [8]),  $\preceq$  and  $\leq$  are quasi-orders on CA and therefore constitute natural candidates for the **divide** relation of bulking axiomatics (definition 8 of [8]).

Inspired by definition 14 of [8], we now define 3 bulking quasi-orders using  $\tilde{\text{PCS}}$  transforms.

**Definition 2.1.**  $\mathcal{B}$  simulates  $\mathcal{A}$  injectively, denoted  $\mathcal{A} \preccurlyeq_i \mathcal{B}$ , if there exist two  $\tilde{\text{PCS}}$  transforms  $\alpha$  and  $\beta$  such that  $\mathcal{A}^{(\alpha)} \sqsubseteq \mathcal{B}^{(\beta)}$ .

We will occasionally use the notion of simulation by grouping introduced in [24] and discussed in [8]: we denote by  $\mathcal{A} \leq_{\square} \mathcal{B}$  the fact that there are  $n$  and  $m$  such that  $\mathcal{A}^{[n]} \sqsubseteq \mathcal{B}^{[m]}$ . This is a special case of the injective simulation above.

**Definition 2.2.**  $\mathcal{B}$  simulates  $\mathcal{A}$  surjectively, denoted  $\mathcal{A} \preccurlyeq_s \mathcal{B}$ , if there exist two  $\tilde{\text{PCS}}$  transforms  $\alpha$  and  $\beta$  such that  $\mathcal{A}^{(\alpha)} \trianglelefteq \mathcal{B}^{(\beta)}$ .

**Definition 2.3.**  $\mathcal{B}$  simulates  $\mathcal{A}$  in a mixed way, denoted  $\mathcal{A} \preccurlyeq_m \mathcal{B}$ , if there exist two  $\tilde{\text{PCS}}$  transforms  $\alpha$  and  $\beta$  such that  $\mathcal{A}^{(\alpha)} \trianglelefteq \mathcal{B}^{(\beta)}$ .

For each notion of simulation above, we say that the simulation is *strong* if the transformation  $\alpha$  applied to the simulated CA is trivial:  $\alpha = \langle 1, 1, 1, 0 \rangle$  so that  $\mathcal{A}^{(\alpha)} = \mathcal{A}$ .

**Theorem 2.2.**  $(CA, \preccurlyeq_i)$ ,  $(CA, \preccurlyeq_s)$  and  $(CA, \preccurlyeq_m)$  are quasi-orders.

PROOF. We show that  $\preccurlyeq_i$  and  $\preccurlyeq_m$  correspond exactly to models of bulking developed in [8]: the proof of theorem 15 of [8] contains the case of injective simulation. The case of  $\preccurlyeq_m$  follows immediately (axiom  $(B_4)$  is straightforward and axiom  $(B_5)$  is verified because  $\trianglelefteq$  contains  $\sqsubseteq$ ). For  $\preccurlyeq_s$ , the proof of each axiom is similar except for axiom  $(B_5)$ .

With or without axiom  $(B_5)$ , theorem 10 of [8] can be applied in each case and show the present theorem.  $\blacksquare$

**Lemma 2.1.** Let  $\triangleleft$  be any relation among  $\sqsubseteq$ ,  $\trianglelefteq$  and  $\trianglelefteq$ . Then the following propositions are equivalent:

- there exist two  $\tilde{\text{PCS}}$  transforms  $\alpha$  and  $\beta$  such that  $\mathcal{A}^{(\alpha)} \triangleleft \mathcal{B}^{(\beta)}$ ,
- there exist a  $\tilde{\text{PCS}}$  transform  $\alpha$  and an integer  $t$  such that  $\mathcal{A}^{(\alpha)} \triangleleft \mathcal{B}^{[t]}$ ,
- there exist a  $\tilde{\text{PCS}}$  transform  $\beta$  and an integer  $t$  such that  $\mathcal{A}^{[t]} \triangleleft \mathcal{B}^{(\beta)}$ ,

PROOF. We use the property of compatibility of relation  $\triangleleft$  with respect to geometrical transforms (axiom  $B_4$  of [8]). The lemma follows from the following property: for any transform  $\alpha$ , there exist a transform  $\beta$  and an integer  $t$  such that

$$\forall F : (F^{(\alpha)})^{(\beta)} = F^{[t]}.$$

If  $\alpha = \langle m, t, z, 0 \rangle$ ,  $\beta$  can be chosen as the composition of  $\langle 1, m, 0, 0 \rangle$ ,  $\langle 1, 1, -z, 0 \rangle$  and  $\langle t, 1, 0, 0 \rangle$ .  $\blacksquare$

In the sequel, if  $\preccurlyeq$  denotes a simulation quasi-order we denote by  $\sim$  the induced equivalence relation and by  $[\mathcal{A}]$  the equivalence class of  $\mathcal{A}$  with respect to  $\sim$ . For instance, to  $\preccurlyeq_i$  we associate the notations  $\sim_i$  and  $[\mathcal{A}]_i$  with the following meanings:

$$\begin{aligned} \mathcal{A} \sim_i \mathcal{B} &\iff \mathcal{A} \preccurlyeq_i \mathcal{B} \text{ and } \mathcal{B} \preccurlyeq_i \mathcal{A}, \\ [\mathcal{A}]_i &= \{\mathcal{B} : \mathcal{A} \sim_i \mathcal{B}\}. \end{aligned}$$

We use similar notations for  $\preceq_s$  and  $\preceq_m$ .

Before entering into details concerning various aspects of the three simulation relations defined above, we can already make a clear (yet informal) distinction between  $\preceq_i$  and  $\preceq_m$  on one hand, and  $\preceq_s$  on the other hand. For the two former, the simulation takes place on a subset of configurations and nothing can be said *a priori* about the behavior of the simulator outside this subset of configurations. For  $\preceq_s$ , however, the simulation occurs on any configuration and the simulator's behavior on any configuration is in some way affected by the simulation. Section 4.2 give several illustrations of this difference.

## 2.2. First Properties

We now establish a set of basic general facts about  $\preceq_i$ ,  $\preceq_s$  and  $\preceq_m$  while next sections of the paper focus on particular aspects.

**Theorem 2.3.** *Let  $\mathcal{A}$  be any CA and  $\preceq$  be any relation among  $\preceq_i$ ,  $\preceq_s$  and  $\preceq_m$ . Then it holds:*

1. *there is some  $\mathcal{B} \in [\mathcal{A}]$  having a quiescent state,*
2. *there is some  $\mathcal{B} \in [\mathcal{A}]$  with radius 1,*
3.  *$\perp \preceq \mathcal{A}$  where  $\perp$  is the CA with a single state,*
4.  *$\mathcal{A} \preceq \mathcal{A} \times \mathcal{B}$  and  $\mathcal{A} \preceq \mathcal{B} \times \mathcal{A}$  for any  $\mathcal{B}$ .*

PROOF.

1. there exists some uniform configuration  $x$  and some  $t \geq 1$  such that  $G_{\mathcal{A}}^t(x) = x$ . So  $\mathcal{A}^t$  has a quiescent state and it clearly belongs to  $[\mathcal{A}]$ .
2.  $\mathcal{A}^{(r_{\mathcal{A}}, 1, 1, 0)}$  admits a syntactical representation with radius 1 and clearly belongs to  $[\mathcal{A}]$ .
3. First, one always has  $\perp \leq_{\pi} \mathcal{A}$  where  $\pi$  is the trivial surjection mapping each state of  $\mathcal{A}$  to the single state of  $\perp$ . So assertion 3 is proven for  $\preceq_s$  and  $\preceq_m$ . Second, one has  $\perp \sqsubseteq_i \mathcal{B}$  if  $\mathcal{B}$  has a quiescent state where  $i$  is the trivial injection mapping the single state of  $\perp$  to the quiescent state of  $\mathcal{B}$ . Assertion 3 follows for  $\preceq_i$  by assertion 1.
4. We show only the first relation, the second being rigorously symmetric. First, one has always  $\mathcal{A} \leq_{\pi_1} \mathcal{A} \times \mathcal{B}$  where  $\pi_1 : S_{\mathcal{A}} \times S_{\mathcal{B}} \rightarrow S_{\mathcal{A}}$  is the projection over the first component. Second, if  $\mathcal{B}$  has a quiescent state  $q$ , one has  $\mathcal{A} \sqsubseteq_{\iota} \mathcal{A} \times \mathcal{B}$  where  $\iota$  is the injection defined by  $\iota(x) = (x, q)$  for all  $x \in S_{\mathcal{A}}$  (the equality  $\bar{\iota} \circ G_{\mathcal{A}} = (G_{\mathcal{A}} \times G_{\mathcal{B}}) \circ \bar{\iota}$  is true over  $S_{\mathcal{A}}^{\mathbb{Z}}$ ). If  $\mathcal{B}$  has no quiescent state, just consider  $\mathcal{B}^t$  and apply the previous reasoning to obtain:

$$\mathcal{A}^t \sqsubseteq \mathcal{A}^t \times \mathcal{B}^t = (\mathcal{A} \times \mathcal{B})^t$$

and thus  $\mathcal{A} \preceq_i \mathcal{A} \times \mathcal{B}$ . ■

The three simulation quasi-orders are derived through bulking axiomatics from three different relations on local rules (see 2.1). There is *a priori* no reason why the differences between local relations should extend to differences between the three simulation quasi-orders. The following theorem shows that  $\preceq_i$ ,  $\preceq_s$  and  $\preceq_m$  are nevertheless different and that  $\preceq_i$  and  $\preceq_s$  are both strictly included in  $\preceq_m$ .

**Theorem 2.4.** *The relations  $\preceq_i$  and  $\preceq_s$  are incomparable (no inclusion in either direction).*

PROOF. We first show that there are CA  $\mathcal{A}$  and  $\mathcal{B}$  such that  $\mathcal{A} \sqsubseteq \mathcal{B}$  but  $\mathcal{A} \not\preceq_s \mathcal{B}$ . Let  $\mathcal{A} = \sigma \times \sigma^{-1}$  defined over states set  $S_{\mathcal{A}} = \{0, 1\} \times \{0, 1\}$  and let  $\mathcal{B}$  be the CA of radius 1 defined over  $S_{\mathcal{B}} = S_{\mathcal{A}} \cup \{\#\}$  by:

$$f_{\mathcal{B}}(x, y, z) = \begin{cases} f_{\mathcal{A}}(x, y, z) & \text{if } x, y, z \in S_{\mathcal{A}}, \\ y & \text{else.} \end{cases}$$

One clearly has  $\mathcal{A} \sqsubseteq_{Id} \mathcal{B}$ . Now suppose  $\mathcal{A} \preceq_s \mathcal{B}$ . Without loss of generality we can assume that there are geometrical transforms  $\alpha = \langle m, \tau, T, s \rangle$  and  $\beta = \langle m', 1, T', 0 \rangle$  such that  $\mathcal{A}^{(\alpha)} \sqsubseteq_{\pi} \mathcal{B}^{(\beta)}$ . But, by definition of  $\mathcal{B}$ , there exists some state  $q_0$  of  $\mathcal{B}^{(\beta)}$  (for instance  $\#^{m'}$ ) which is left invariant by iteration of  $\mathcal{B}^{(\beta)}$  whatever the context. Then  $\pi(q_0)$  must be a state of  $\mathcal{A}^{(\alpha)}$  with the same property. This is impossible since either  $s \neq T$  or  $s \neq -T$  and thus some component of the future state of a cell of  $\mathcal{A}^{(\alpha)}$  is dependent of the state of a neighboring cell.

Now we show that there are  $\mathcal{A}$  and  $\mathcal{B}$  such that  $\mathcal{A} \sqsubseteq \mathcal{B}$  but  $\mathcal{A} \not\preceq_i \mathcal{B}$  and the theorem follows. Let  $\mathcal{A}$  and  $\mathcal{B}$  be the automata pictured on figure 1.  $\mathcal{A}$  is a CA with two states, 0 and 1, whose behavior is to reduce ranges of 1's progressively until they reach size 1: at each time step the cells at each ends of a range of size 3 or more are turned into state 0 (only the right cell of range of size 2 is turned into 0).  $\mathcal{B}$  has three states (0, 1 and 2) and has the following behavior: ranges of size 3 or more of non-zero states are reduced in a similar way by the two ends (states inside ranges are left unchanged), ranges of size 2 become an isolated 2 (left cell becomes 2 and right cell 0), and ranges of size 1 become an isolated 1. In a word,  $\mathcal{B}$  reduces the size of non-zero ranges until size 1 but keeps the parity information at the end: an even range becomes eventually an isolated 2 and an odd range becomes an isolated 1 (see figure 1).

Formally, let  $\pi : \{0, 1, 2\} \rightarrow \{0, 1\}$  be the surjective function defined by  $\pi(0) = 0$  and  $\pi(x) = 1$  if  $x \neq 0$ . Now let  $\mathcal{A}$  be the CA of radius 2 and state set  $S_{\mathcal{A}} = \{0, 1, 2\}$  with local rule:

$$f_{\mathcal{A}}(x, y, z, t, u) = \begin{cases} 1 & \text{if } \pi(xyztu) = 01110, \\ 2 & \text{if } \pi(yztu) = 0110, \\ z & \text{if } \pi(yzt) = 111 \text{ and if } \pi(xyztu) \neq 01110, \\ z & \text{if } \pi(yzt) = 010, \\ 0 & \text{in any other case.} \end{cases}$$

Finally, let  $\mathcal{B}$  be the CA with states set  $B = \{0, 1\}$ , radius 2 and local transition function

$$f_{\mathcal{B}}(x, y, z, t, u) = \begin{cases} 1 & \text{if } yzt = 111 \text{ or } yzt = 010 \text{ or } yztu = 0110, \\ 0 & \text{else.} \end{cases}$$

By construction, we have  $\mathcal{A} \sqsubseteq_{\pi} \mathcal{B}$ . Now suppose for the sake of contradiction that  $\mathcal{A} \preceq_i \mathcal{B}$  and more precisely:

$$\mathcal{A}^{(m', \tau', t', s')} \sqsubseteq_{\phi} \mathcal{B}^{(m, 1, t, 0)},$$





Figure 1: Behavior of  $\mathcal{A}$  (left) and  $\mathcal{B}$  (right). Time goes from bottom to top.

where  $\alpha = \langle m', \tau', t', s' \rangle$  and  $\beta = \langle m, 1, t, 0 \rangle$  are suitable geometrical transforms. Let  $u = 1^{m'}$  and  $v = 0^{m'}$  ( $u$  and  $v$  are particular states of  $\mathcal{A}^{(\alpha)}$ ) and consider  $U = \phi(u)$  and  $V = \phi(v)$  ( $U$  and  $V$  belong to  $S_{\mathcal{B}}^{m'}$ ). The remaining of the proof below proceeds by a careful case analysis on  $U$  and  $V$  to obtain a final contradiction. The main technique is to consider specific orbits of  $\mathcal{A}^{(\alpha)}$  involving  $u$  and  $v$ , and to derive constraints on their possible image by  $\phi$  involving  $U$  and  $V$ .

Since configurations  $\bar{u}$  and  $\bar{v}$  are fixed points of  $\mathcal{A}^{(\alpha)}$ , so are  $\bar{U}$  and  $\bar{V}$  for  $\mathcal{B}^{(\beta)}$ . Moreover, one can check from the definition above that the state 0 is a 'blocking state' for  $\mathcal{B}$ : the half-configuration on the left of an occurrence of 0 evolves independently of the half-configuration on its right. So, if  $U$  contains one or more zero's, then any configuration of  $\mathcal{B}^{(\beta)}$  containing  $U^3$  will contain at least one occurrence of  $U$  for ever (because it is the case for the configuration  $\bar{U}$ ): this is in contradiction with the fact that the orbit of a configuration of the form  ${}^\omega v u^4 v^\omega$  does not contain any occurrence of  $u$  after sufficiently many iterations of  $\mathcal{A}^{(\alpha)}$  (because, whatever the value of  $m'$ ,  $u^4$  represents in  $\mathcal{A}$  an even-sized range of 1s which is reduced until the last two 1s are turned into a single 2 by case 2 of the definition of  $\mathcal{A}$ ). Hence we have  $\bar{\pi}(U) = 1^m$ .

From this we deduce that  $V = 0^m$  because configurations of the form  ${}^\omega V U^n V^\omega$  are transformed into configurations where a single cell is not in state  $V$  (just consider the orbit of  ${}^\omega v u v^\omega$  under  $\mathcal{A}^{(\alpha)}$ ) and large ranges of non-zero states are always turned into large ranges of zero's under  $\mathcal{B}$ .

Finally, we have  $\bar{\pi}(\phi(0^{m'-1}1)) = 0^{m-1}1$  by considering the orbit of a configuration of the form  ${}^\omega v u^2 v^\omega$  under  $\mathcal{A}^{(\alpha)}$  and its counterpart of the form  ${}^\omega V U^2 V^\omega$  under  $\mathcal{B}^{(\beta)}$  (by the way, we also show that the shift parameter of transform  $\alpha$  is 0). Now, letting  $u' = 0^{m'-1}1$ , we have on one hand the orbits of 2 configurations of the form  ${}^\omega v u' u^{2n} v^\omega$  and  ${}^\omega v u^{2n} v^\omega$  both leading to the same configuration of the form  ${}^\omega v u' v^\omega$  under  $\mathcal{A}^{(\alpha)}$ , and on the other hand, the orbits of  ${}^\omega V \phi(u') U^{2n} V^\omega$  and  ${}^\omega V U^{2n} V^\omega$  leading to different fixed points under  $\mathcal{B}^{(\beta)}$  due to different parity of non-zero ranges: this is a contradiction since  $\bar{\phi} \circ \mathcal{A}^{(\alpha)} = \mathcal{B}^{(\beta)} \circ \bar{\phi}$ . ■

### 3. Bottoms of the Orders

This section focuses on the bottom of the orders. We have already seen (theorem 2.3) that  $\perp$  is a global minimum for the three quasi-orders considered here. In this section, we study CA that are at the lowest *levels* of the quasi-orders. Formally, the only CA at level 0 is  $\perp$  and a CA  $\mathcal{A}$  is at level  $n+1$  for a quasi-order  $\preceq$  if:

1.  $\mathcal{A}$  is not at level  $n$  and,
2.  $\forall \mathcal{B} : \mathcal{B} \preccurlyeq \mathcal{A} \Rightarrow \mathcal{B} \in [\mathcal{A}]$  or  $\mathcal{B}$  is at level  $i$  with  $i \leq n$ .

The following theorem shows that some classical properties of CA correspond to classes at level 1. Recall that a cellular automaton is nilpotent if all initial configurations lead to the same configuration after a finite time.

**Theorem 3.1.** *Let  $\preccurlyeq$  be a simulation relation among  $\preccurlyeq_i$ ,  $\preccurlyeq_s$  and  $\preccurlyeq_m$ . Then the following CA are at level 1 (provided they have 2 or more states):*

1. *the set of nilpotent CA, which is an equivalence class for  $\sim$ ,*
2. *the set of CA which are periodic up to translation ( $\mathcal{A}^t \circ \sigma_z = Id$ ) which is exactly the equivalence class for  $\sim$  of the identity CA.*

PROOF.

1. Nilpotency is equivalent to the existence of a uniform configuration reached in a fixed finite time from any configuration. This property of phase space is clearly invariant by geometrical transforms and preserved by taking sub-automata or quotient automata. So any nilpotent CA is at level at most 1. Moreover, the set of nilpotent CA forms an equivalence class. Indeed, for any nilpotent  $\mathcal{A}$ , there is  $t$  such that  $\mathcal{A}^t$  is a constant function equal to some  $\overline{q_a}$ . If we consider any nilpotent  $\mathcal{B}$  with at least 2 states, there is  $m$  such that  $|S_{\mathcal{B}}^m| \geq |S_{\mathcal{A}}|$  and  $t'$  such that  $\mathcal{B}^{t'}$  is a constant function equal to some  $\overline{q_b}$ . If we consider the geometrical transforms  $\alpha = \langle 1, 1, t, 0 \rangle$  and  $\beta = \langle m, 1, t', 0 \rangle$ , then we have both  $\mathcal{A}^{(\alpha)} \sqsubseteq_i \mathcal{B}^{(\beta)}$  and  $\mathcal{A}^{(\alpha)} \preccurlyeq_\pi \mathcal{B}^{(\beta)}$  if  $i$  is such that  $i(q_a) = q_b$  and  $\pi$  is such that  $\pi(x) = q_a \iff x = q_b$ .
2. Any CA which is periodic up to a translation is by definition equivalent to some identity CA and two identity CA with different state set are also clearly equivalent. Moreover, all such CA are at level 1 because the property of being periodic up to translations is preserved by geometrical transformations and by taking sub-automata or quotient automata. ■

In the remaining part of this section, we will study two families of cellular automata with respect to the quasi-orders: a subset of additive CA and products of shifts. Our goal is to show that at (almost) each finite level there are infinitely many incomparable classes (theorem 3.3 and corollary 3.1 below).

### 3.1. Additive Cellular Automata

The bottom of the quasi-order  $\leq_\square$  was studied in [24]. The main result is the existence of an infinite family of mutually incomparable CA at level 1: the family of CA  $\mathcal{Z}_p$  with  $p$  a prime number and where  $\mathcal{Z}_p$  is a CA of radius 1 and state set  $\{0, \dots, p-1\}$  defined by the following local rule:

$$\delta_{\mathcal{Z}_p}(x, y, z) = x + y + z \bmod p.$$

There are strong connections between  $\leq_\square$  and  $\preccurlyeq_i$  and in fact the set of CA at level 1 are the same for these two quasi-orders.

**Lemma 3.1.** *If  $\mathcal{A}$  is at level 1 for  $\leq_\square$  then  $\mathcal{A}$  is at level 1 for  $\preccurlyeq_i$ .*

PROOF. If  $\mathcal{B} \preceq_i \mathcal{A}$  then by lemma 2.1 there is some integer  $t$  and some transform  $\beta$  such that  $\mathcal{B}^{(\beta)} \subseteq \mathcal{A}^{[t]}$ . By theorem 2.3 we can suppose that  $\mathcal{A}$  has radius 1 so  $\mathcal{B}^{(\beta)}$  has radius 1. Since  $\mathcal{A}$  is at level 1 for  $\leq_\square$ , then either  $\mathcal{B}^{(\beta)} \in [\mathcal{A}]_\square$  or  $\mathcal{B}^{(\beta)} \in [\perp]_\square$ . We deduce that either  $\mathcal{B} \in [\mathcal{A}]_i$  or  $\mathcal{B} \in [\perp]_i$ . Hence  $\mathcal{A}$  is at level at most 1 for  $\preceq_i$  and it cannot be at level 0 since it is not in  $[\perp]_i = [\perp]_\square$ . ■

The previous lemma is not enough to show that the CA  $(\mathcal{Z}_p)_p$  with  $p$  prime are mutually  $\preceq_i$ -incomparable because several equivalence classes for  $\leq_\square$  can be included in a single class for  $\preceq_i$ . However we are going to show that this family is a set of mutually incomparable CA for the three quasi-orders introduced above<sup>2</sup>. Moreover, for  $\leq_\square$  and  $\preceq_i$ , they are all at level 1. The proof relies on the following result already used for the case of  $\leq_\square$ .

A CA  $(S, r, f)$  is *LR-permutative* if the two following functions are bijections for all  $a_1, \dots, a_{2r}$ :

- $x \mapsto f(a_1, \dots, a_{2r}, x)$  and
- $x \mapsto f(x, a_1, \dots, a_{2r})$ .

**Theorem 3.2 ([22]).** *Let  $p$  be a prime number and  $t \geq 1$ . Then we have:*

1.  $\mathcal{Z}_p^{[t]}$  is LR-permutative;
2. if  $\mathcal{A} \subseteq \mathcal{Z}_p^{[t]}$  then  $p$  divides  $|S_{\mathcal{A}}|$ .

To take into account use of  $\leq$  in simulation we will use the following lemma.

**Lemma 3.2.** *If  $\mathcal{B}$  is LR-permutative and  $\mathcal{A} \leq \mathcal{B}$  then  $|S_{\mathcal{A}}|$  divides  $|S_{\mathcal{B}}|$ .*

PROOF. To simplify notations, we suppose that  $\mathcal{B}$  is of radius 1 (the proof works the same way for higher radii). Suppose  $\mathcal{A} \leq_\pi \mathcal{B}$ . By surjectivity of  $\pi$ , it is sufficient to show that  $\pi$  is balanced, *i.e.* such that for all  $x, y \in S_{\mathcal{A}}$ :

$$|\{e : \pi(e) = x\}| = |\{e : \pi(e) = y\}|.$$

Consider any  $x, y \in S_{\mathcal{A}}$ . Let  $a, b \in S_{\mathcal{B}}$  be such that  $\pi(a) = x$  and  $\pi(b) = y$  and consider any  $c \in S_{\mathcal{B}}$ . By R-permutativity there is  $d \in S_{\mathcal{B}}$  such that  $f_{\mathcal{B}}(a, c, d) = b$ . Now for any  $a' \in S_{\mathcal{B}}$  such that  $\pi(a') = \pi(a)$ , we must have  $\pi(f_{\mathcal{B}}(a', c, d)) = \pi(b)$  because  $\mathcal{A} \leq_\pi \mathcal{B}$ . Moreover, by L-permutativity,  $a' \mapsto f_{\mathcal{B}}(a', c, d)$  is one-to-one which proves:

$$|\{a : \pi(a) = x\}| \leq |\{b : \pi(b) = y\}|.$$

The balance of  $\pi$  follows by symmetry. ■

The results above are the key ingredient of the following theorem.

**Theorem 3.3.** *Let  $\preceq$  be any relation among  $\preceq_i$ ,  $\preceq_s$  and  $\preceq_m$ . Let  $p$  and  $q$  be two distinct prime numbers. Then we have:*

1.  $\mathcal{Z}_p \not\preceq \mathcal{Z}_q$

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<sup>2</sup>The proof we give here was suggested by E. Jeandel.

2.  $\mathcal{Z}_p$  is at level 1 for  $\preceq_i$ ;

PROOF. 2 follows immediately from lemma 3.1 and the fact that  $\mathcal{Z}_p$  is at level 1 for  $\leq_\square$  (corollary 2 of [22]). To prove assertion 1 it is enough to prove  $\mathcal{Z}_p \not\prec_m \mathcal{Z}_q$ . Suppose for the sake of contradiction that  $\mathcal{Z}_p \prec_m \mathcal{Z}_q$ , or equivalently by lemma 2.1, that there are a CA  $\mathcal{A}$ , a transform  $\alpha$  and an integer  $t$  such that  $\mathcal{Z}_p^{(\alpha)} \leq \mathcal{A} \subseteq \mathcal{Z}_q^{[t]}$ . Then, combining lemma 3.2 and theorem 3.2, we deduce that the number of states of  $\mathcal{Z}_p^{(\alpha)}$  is a power of  $q$  which contradicts the fact that  $p$  and  $q$  are two distinct primes. ■

### 3.2. Products of Shifts

We will now study products of shifts in order to show that there are infinitely many incomparable CA at any finite level greater than 3 for any of the three simulation quasi-orders of the paper.

We denote by  $\sigma_{n,z}$  the translation CA with  $n$  states  $\{1, \dots, n\}$  and translation vector  $z$  defined by:

$$\sigma_{n,z}(c)_{z'} = c_{z'-z}.$$

We then consider cartesian products of such CA. Since  $\sigma_{n,z} \times \sigma_{p,z} \equiv \sigma_{np,z}$ , we can focus on considering cartesian products where all vectors are distinct.

The next lemma shows that the structure of product of translations is preserved when taking sub-automata and quotient-automata.

**Lemma 3.3.** *Let  $\mathcal{B} = \prod_{i=1}^p \sigma_{n_i, z_i}$  (with  $z_i$  all distinct) and suppose  $\mathcal{A}$  is such that  $\mathcal{A} \leq \mathcal{B}$  then  $\mathcal{A}$  is isomorphic to  $\prod_{j=1}^k \sigma_{n'_{i_j}, z_{i_j}}$  where  $1 \leq i_j \leq n$  and  $2 \leq n'_{i_j} \leq n_{i_j}$ .*

PROOF. The lemma is straightforward if we replace  $\leq$  by  $\sqsubseteq$ . So it is enough to show that it is also true when replacing  $\leq$  by  $\trianglelefteq$ . Suppose that  $\mathcal{A} \trianglelefteq_\pi \mathcal{B}$ . The idea of the proof is to show that  $\pi$  must be 'compatible' with the product structure: it forgets some components and keeps others but never introduces any kind of 'correlation' between them. So let  $i$  be such a component in  $\mathcal{B}$  ( $1 \leq i \leq p$ ). Consider any pair of states  $q, q' \in S_{\mathcal{B}}$  such that  $q_i = q'_i$  (where  $q_i$  or  $q'_i$  denotes the projection on the  $i$ th component). Denote by  $q_+$  and  $q'_+$  the states obtained from  $q$  and  $q'$  by changing their  $i$ th component in the same way ( $(q_+)_i = (q'_+)_i$ ). Since the  $z_i$  are distinct, one can build two configurations  $c$  and  $c'$  of  $\mathcal{B}$  such that:

- $c(z) = c'(z)$  for all  $z \neq 0$ ,
- $c(0) = q$  and  $c'(0) = q'$ ,
- $\mathcal{B}(c)_0 = q_+$  and  $\mathcal{B}(c')_0 = q'_+$ .

If  $\pi(q) = \pi(q')$  we have  $\bar{\pi}(c) = \bar{\pi}(c')$  so  $\pi(q_+) = \pi(q'_+)$ . The same reasoning can be done starting from  $q_+$  and  $q'_+$  so we have:

$$\pi(q) = \pi(q') \iff \pi(q_+) = \pi(q'_+)$$

Hence, if there exist two states  $e$  and  $e'$  with the same image by  $\pi$  and which agree on all components except component  $i$ , then values  $e_i$  and  $e'_i$  can be exchanged in the  $i$ th component of any state without affecting its image by

$\pi$ . In such a case, we can consider the CA  $\mathcal{C}$  obtained from  $\mathcal{B}$  by identifying  $e_i$  and  $e'_i$  in the  $i$ th component. More precisely,  $\mathcal{C}$  is of the form

$$\mathcal{C} = \prod_{j=1}^p \sigma_{n'_j, z_j}$$

with  $n'_i = n_i - 1$  and  $n'_j = n_j$  for any  $j \neq i$ . Then we have  $\mathcal{A} \trianglelefteq \mathcal{C} \trianglelefteq \mathcal{B}$ . Applying this reasoning iteratively, we finally have  $\mathcal{A} \trianglelefteq_g \mathcal{C}_0 \trianglelefteq \mathcal{B}$  where  $\mathcal{C}_0$  is of the form  $\prod_{j=1}^k \sigma_{n'_{i_j}, z_{i_j}}$  where  $1 \leq i_j \leq n$  and  $2 \leq n'_{i_j} \leq n_{i_j}$  (component reduced to 1 state during one step of the process can be eliminated) and  $g$  is such that changing the value of any component of any state of  $\mathcal{C}_0$  will change its image by  $g$ . Now suppose for the sake of contradiction that  $g$  is not injective. Then there are states  $q$  and  $q'$  of  $\mathcal{C}_0$  such that  $g(q) = g(q')$ . Let  $c = \overline{q}$  and  $c'$  be equal to  $c$  except on position 0 where it is in state  $q'$ . By hypothesis, at any position  $z$ ,  $G_{\mathcal{C}_0}(c)$  and  $G_{\mathcal{C}_0}(c')$  must be in states having the same image by  $g$ . But since  $\mathcal{C}_0$  is a product of translations with distinct vectors, there must be some position  $z$  where  $G_{\mathcal{C}_0}(c)$  and  $G_{\mathcal{C}_0}(c')$  are in states which differ on one component only: this is in contradiction with the hypothesis on  $g$ . Hence  $g$  is injective and therefore  $\mathcal{A} \equiv \mathcal{C}_0$ .  $\blacksquare$

We will now study the effects of geometrical transformations on CA which are products of shifts. Of course, the translation vectors involved in such an automaton can be altered by geometrical transformations. If  $\mathcal{A}$  is a product of translations with vectors  $z_1 < \dots < z_a$ , we denote by  $\chi(\mathcal{A})$  the following characteristic sequence (provided  $a \geq 3$ ):

$$\chi(\mathcal{A}) = \left( \frac{z_3 - z_1}{z_2 - z_1}, \dots, \frac{z_a - z_1}{z_2 - z_1} \right).$$

The purpose of the following theorem and lemma is to establish that the characteristic sequence gives a simple way to compare any pair of products of shifts in the three quasi-orders.

**Theorem 3.4.** *Let  $\preccurlyeq$  be a relation among  $\preccurlyeq_i$ ,  $\preccurlyeq_s$  and  $\preccurlyeq_m$ . Let  $\mathcal{A}$  be a product of  $a \geq 3$  translations with distinct vectors and with characteristic sequence  $\chi(\mathcal{A}) = (\alpha_1, \dots, \alpha_{a-2})$ . If  $\mathcal{B} \preccurlyeq \mathcal{A}$  then  $\mathcal{B}$  is equivalent to some  $\mathcal{C}$  which is a product of a subset of  $b$  translations of  $\mathcal{A}$ . Moreover, we have the following properties:*

1. *if  $b = a$  then  $\mathcal{C}$  has the same characteristic sequence than  $\mathcal{A}$ ;*
2. *if  $b = a - 1$  and  $b \geq 3$  then the characteristic sequence of  $\mathcal{C}$  has one of the following form:*
  - $(\alpha_1, \dots, \alpha_{i-1}, \alpha_{i+1}, \dots, \alpha_{a-2})$
  - $\left( \frac{\alpha_2}{\alpha_1}, \dots, \frac{\alpha_{a-2}}{\alpha_1} \right)$
  - $\left( \frac{\alpha_2 - 1}{\alpha_1 - 1}, \dots, \frac{\alpha_{a-2} - 1}{\alpha_1 - 1} \right)$
3. *if the characteristic sequence of  $\mathcal{C}$  is not  $\chi(\mathcal{A})$  then  $\mathcal{A} \not\preccurlyeq \mathcal{C}$ .*

PROOF. Let  $z_1 < z_2 < \dots < z_a$  be the ordered list of translation vectors of  $\mathcal{A}$ . Since  $\mathcal{B} \preceq \mathcal{A}$ , there is some  $\mathcal{C}$  equivalent to  $\mathcal{B}$  and some integer  $t \geq 1$  such that  $\mathcal{C} \subseteq \mathcal{A}^{[t]}$  (by lemma 2.1). We deduce from lemma 3.3 that  $\mathcal{C}$  is isomorphic to a product of translations whose vectors are a subset of the family  $(z_i)$  since  $\mathcal{A}$  and  $\mathcal{A}^{[t]}$  have identical translation vectors,  $\mathcal{C}$  must have the same characteristic sequence than  $\mathcal{A}$  if it has the same number of translation vectors. When  $b = a - 1$  and  $b \geq 3$ , it is straightforward to check that the three possible forms of the characteristic sequence of  $\mathcal{C}$  correspond to the case where the missing vector is  $z_i$ ,  $z_2$  and  $z_1$  respectively. To prove the last assertion of the theorem, it is sufficient to check that for any transform  $\alpha$  of the form  $\langle m, 1, mt, mz \rangle$  (we can restrict to such transforms by lemma 2.1,  $\mathcal{C}$  and  $\mathcal{C}^{(\alpha)}$  are products of translations with the same characteristic sequence because each vector  $z_i$  of  $\mathcal{C}$  becomes  $tz_i + z$  in  $\mathcal{C}^{(\alpha)}$ ). ■

The next lemma gives canonical members of the equivalence classes of products of shifts.

**Lemma 3.4.** *Let  $\sim$  be the equivalence relation induced by any of the quasi-order  $\preceq_i$ ,  $\preceq_s$  and  $\preceq_m$ . Consider any  $t \neq 0$ , any  $z$  and any product of translations of the form  $\mathcal{A} = \prod_{i=1}^p \sigma_{n_i, tz_i + z}$ . Then we have:*

$$\mathcal{A} \sim \prod_{1 \leq i \leq p} \sigma_{2, z_i}$$

PROOF. Let  $\mathcal{B} = \prod_{i=1}^p \sigma_{2, z_i}$  and let  $m = \max n_i$ . It is straightforward to check that  $\mathcal{A} \preceq \mathcal{B}^{\langle m, 1, mt, mz \rangle}$  and  $\mathcal{A} \subseteq \mathcal{B}^{\langle m, 1, mt, mz \rangle}$ , and also that  $\mathcal{B}^{\langle 1, 1, t, z \rangle} \preceq \mathcal{A}$  and  $\mathcal{B}^{\langle 1, 1, t, z \rangle} \subseteq \mathcal{A}$ . ■

Theorem 3.4 and lemma 3.4 give a complete characterisation of the position of products of shifts in the quasi-orders considered in this paper. We will use it later in section 4.1 but we now state the main result of this section concerning levels at the bottom of the quasi-orders.

**Corollary 3.1.** *Let  $\preceq$  be a relation among  $\preceq_i$ ,  $\preceq_s$  and  $\preceq_m$ . For any  $n \geq 3$ , there are infinitely many incomparable CA at level  $n$  for  $\preceq$ .*

PROOF. We have shown in theorem 3.1 that translations CA are at level 1. Lemma 3.3 together with lemma 3.4 show that a product of two translations (with distinct vectors) is at level 2. By theorem 3.4 we conclude that any product of  $n$  translations with distinct vectors is at level  $n$  and two such CA are incomparable if they have different characteristic sequences provided  $n \geq 3$ . ■

#### 4. Structural properties

In this section we study in various ways the order structures induced by the simulation relations defined above.

#### 4.1. Cartesian Products and Lack of (Semi-)Lattice Structure

The Cartesian Product of cellular automata is not a neutral operation from the point of view of the three quasi-orders of the paper. For instance, there are CA  $\mathcal{A}$ ,  $\mathcal{B}$  which are equivalent but such that  $\mathcal{A} \times \mathcal{A}$  is not equivalent to  $\mathcal{B} \times \mathcal{A}$  (it is sufficient to take two shifts with different translation vectors).

The next theorem shows however that some simulations by Cartesian products of CA can be transposed to components of the product.

**Theorem 4.1.** *Let  $\mathcal{A}$  be a CA with two states and let  $\preceq$  be a simulation relation among  $\preceq_i$ ,  $\preceq_s$  and  $\preceq_m$ . For any  $\mathcal{B}$  and  $\mathcal{C}$ , if  $\mathcal{B} \times \mathcal{C}$  strongly  $\preceq$ -simulates  $\mathcal{A}$  then either  $\mathcal{A} \preceq \mathcal{B}$  or  $\mathcal{A} \preceq \mathcal{C}$ .*

Notice that the 'two states' and 'strong simulation' hypotheses are both important and related. The theorem doesn't hold without such hypotheses: take two shifts with different vectors for  $\mathcal{B}$  and  $\mathcal{C}$  and choose  $\mathcal{A} = \mathcal{B} \times \mathcal{C}$ .

PROOF (OF THE THEOREM). Let  $S_{\mathcal{A}} = \{a_1, a_2\}$ . First, we show that  $\mathcal{A} \sqsubseteq_{\iota} \mathcal{B} \times \mathcal{C}$  implies either  $\mathcal{A} \sqsubseteq \mathcal{B}$  or  $\mathcal{A} \sqsubseteq \mathcal{C}$  which is sufficient to prove the theorem for  $\preceq_i$  and  $\preceq_m$ . Since  $\iota(a_1) \neq \iota(a_2)$  we have either  $\pi_1(i(a_1)) \neq \pi_1(i(a_2))$  or  $\pi_2(i(a_1)) \neq \pi_2(i(a_2))$  where  $\pi_1$  and  $\pi_2$  are projections over first and second component respectively. We suppose the first case (the second is symmetric) and so  $\pi_1 \circ i : S_{\mathcal{A}} \rightarrow S_{\mathcal{B}}$  is injective. Moreover, since

$$\overline{\pi_1 \circ \iota} \circ G_{\mathcal{A}} = \overline{\pi_1} \circ G_{\mathcal{B} \times \mathcal{C}} \circ \overline{\iota} = G_{\mathcal{B}} \circ \overline{\pi_1 \circ \iota},$$

we conclude that  $\mathcal{A} \sqsubseteq_{\pi_1 \circ \iota} \mathcal{B}$ .

Second, we show that  $\mathcal{A} \sqsubseteq_s \mathcal{B} \times \mathcal{C}$  implies either  $\mathcal{A} \preceq_s \mathcal{B}$  or  $\mathcal{A} \preceq_s \mathcal{C}$  which is sufficient to prove the theorem for  $\preceq_s$ . Let  $I_{\mathcal{A}}$  be the set of states that can be reached after one step of  $\mathcal{A}$  (formally,  $I_{\mathcal{A}} = f_{\mathcal{A}}(S_{\mathcal{A}}, \dots, S_{\mathcal{A}})$ ) and  $I_{\mathcal{B}}$  and  $I_{\mathcal{C}}$  be similar sets for  $\mathcal{B}$  and  $\mathcal{C}$ .

- We first suppose that  $\mathcal{B}$  and  $\mathcal{C}$  are such that each uniform configuration is either a fixed-point or without any uniform antecedent. If  $a_1 \notin I_{\mathcal{A}}$  then for any  $b$  and  $c$  such that  $s(b, c) = a_1$  we have either  $b \notin I_{\mathcal{B}}$  or  $c \notin I_{\mathcal{C}}$ . We suppose the first case (the second is analogous) and then we have  $\mathcal{A} \sqsubseteq_{\zeta} \mathcal{B}$  where  $\zeta : S_{\mathcal{B}} \rightarrow S_{\mathcal{A}}$  is defined by  $\zeta(b) = a_1$  and  $\zeta(x) = a_2$  for  $x \neq b$ .

If  $a_2 \notin I_{\mathcal{A}}$  we apply the same reasoning and so we are left with the case  $I_{\mathcal{A}} = S_{\mathcal{A}}$ . Since pairs of  $S_{\mathcal{B}} \times S_{\mathcal{C}}$  are 2-colored via  $s$ , there must be two pairs of different colors which agree on a component. Suppose it is the first component (the other case is symmetric), we have  $b_1, b_2 \in S_{\mathcal{B}}$  and  $c \in S_{\mathcal{C}}$  such that  $s(b_1, c) = a_1$  and  $s(b_2, c) = a_2$ . Consider the set  $X = \{(b_1, c), (b_2, c)\}$ . Since  $\overline{s} \circ (G_{\mathcal{B}} \times G_{\mathcal{C}}) = G_{\mathcal{A}} \circ \overline{s}$  and  $\overline{s}(X^{\mathbb{Z}}) = S_{\mathcal{A}}^{\mathbb{Z}}$  and  $I_{\mathcal{A}} = S_{\mathcal{A}}$  we necessarily have  $s(S_{\mathcal{B}}, d) = S_{\mathcal{A}}$  where  $d$  defined by  $\overline{d} = G_{\mathcal{C}}(\overline{c})$ .  $d$  is quiescent by hypothesis on  $\mathcal{C}$ . So we have  $\mathcal{A} \sqsubseteq_{\zeta} \mathcal{B}$  with  $\zeta : S_{\mathcal{B}} \rightarrow S_{\mathcal{A}}$  defined by  $\zeta(x) = s(x, d)$  ( $\zeta$  is onto by choice of  $d$ ).

- Now suppose that the hypothesis on  $\mathcal{B}$  and  $\mathcal{C}$  are not fulfilled. Then, if  $t = |S_{\mathcal{B}}|! \times |S_{\mathcal{C}}|!$ , both  $\mathcal{B}^t$  and  $\mathcal{C}^t$  are guaranteed to fulfill the required hypothesis (because any uniform configuration is either in a cycle of uniform configurations, or without uniform antecedent arbitrarily far in the past). Since  $\mathcal{A}^t \sqsubseteq (\mathcal{B} \times \mathcal{C})^t = \mathcal{B}^t \times \mathcal{C}^t$ , it suffices to apply the previous reasoning

on  $\mathcal{A}^t$ ,  $\mathcal{B}^t$  and  $\mathcal{C}^t$  to conclude either  $\mathcal{A}^t \sqsubseteq \mathcal{B}^t$  or  $\mathcal{A}^t \sqsubseteq \mathcal{C}^t$ . In either case the theorem follows.  $\blacksquare$

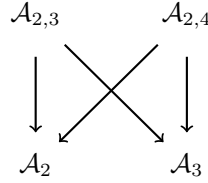
The Cartesian product operation is not a supremum in any of the quasi-order. In fact these quasi-orders don't admit any supremum or infimum operation as shown by the theorem below. Recall that an upper semi-lattice is a partial order structure  $\leq$  equipped with a 'sup' operation such that:

$$a \leq x \text{ and } b \leq x \Rightarrow \sup(a, b) \leq x$$

The definition for lower semi-lattice is dual (replace 'sup' by 'inf' and any relation  $x \leq y$  by  $y \leq x$ ).

**Theorem 4.2.** *Let  $\preccurlyeq$  be a relation among  $\preccurlyeq_i$ ,  $\preccurlyeq_s$  and  $\preccurlyeq_m$ . Then the ordered structure  $(AC/\sim, \preccurlyeq)$  is neither an upper semi-lattice, nor a lower semi-lattice.*

PROOF. Let  $\mathcal{A}_2$ ,  $\mathcal{A}_3$ ,  $\mathcal{A}_{2,3}$  and  $\mathcal{A}_{2,4}$  be products of translations with characteristic sequences (2), (3), (2, 3) and (2, 4) respectively. Theorem 3.4 and lemma 3.4 show that they induce the following structure in  $\preccurlyeq$ :



where an arrow from  $\mathcal{A}$  to  $\mathcal{B}$  means  $\mathcal{B} \preccurlyeq \mathcal{A}$  and if  $\mathcal{B} \preccurlyeq \mathcal{C} \preccurlyeq \mathcal{A}$  then either  $\mathcal{B} \sim \mathcal{C}$  or  $\mathcal{C} \sim \mathcal{A}$ . This shows that the pair  $\mathcal{A}_2, \mathcal{A}_3$  has no supremum and that the pair  $\mathcal{A}_{2,3}, \mathcal{A}_{2,4}$  has no infimum.  $\blacksquare$

#### 4.2. Ideals and Filters

Although the structures  $(AC, \preccurlyeq)$  studied in this paper are not semi-lattices (see above), many classical properties of cellular automata are nicely captured through *ideals* and *filters*. Well-known in lattice theory and algebra, the notions of ideal and filter can also be defined for an arbitrary (quasi-)ordered structure [7]. For the structure  $(AC, \preccurlyeq)$ , an ideal  $I$  is a set of CA such that:

- if  $\mathcal{A} \in I$  and  $\mathcal{B} \preccurlyeq \mathcal{A}$  then  $\mathcal{B} \in I$ ;
- for any  $\mathcal{A}, \mathcal{B} \in I$  there is some  $\mathcal{C} \in I$  such that  $\mathcal{A} \preccurlyeq \mathcal{C}$  and  $\mathcal{B} \preccurlyeq \mathcal{C}$ .

Moreover,  $I$  is said *principal* if there is some  $\mathcal{A}_I$  such that  $\mathcal{A} \in I \iff \mathcal{A} \preccurlyeq \mathcal{A}_I$ . The notion of filter and principal filter are dual of ideal and principal ideal (replacing all  $X \preccurlyeq Y$  by  $Y \preccurlyeq X$ ).

Given a set  $I$  of CA, the three following conditions are sufficient for  $I$  to be an ideal for the simulation  $\preccurlyeq_i$  (resp.  $\preccurlyeq_s$ , or  $\preccurlyeq_m$ ):

1.  $\mathcal{A} \in I \iff \mathcal{A}^{(\alpha)} \in I$  for any transform  $\alpha$ ,
2. if  $\mathcal{B} \in I$  and  $\mathcal{A} \sqsubseteq \mathcal{B}$  (resp.  $\mathcal{A} \leq \mathcal{B}$ , or  $\mathcal{A} \leq \mathcal{B}$ ) then  $\mathcal{A} \in I$ ,
3. if  $\mathcal{A} \in I$  and  $\mathcal{B} \in I$  then  $\mathcal{A} \times \mathcal{B} \in I$ .

Most of the proofs below follow this scheme.



#### 4.2.1. Dynamical properties

The following theorem shows that several dynamical properties of global rules of CA correspond to ideals in the quasi-orders. A CA is nilpotent over periodic configurations if there exists a spatially periodic configuration  $c_0$  such that all spatially periodic configurations lead in finite time to  $c_0$ .

**Theorem 4.3.** *Let  $\preceq$  be a simulation relation among  $\preceq_i$ ,  $\preceq_s$  and  $\preceq_m$ . The following sets of CA form ideals of  $(AC, \preceq)$ :*

- *surjective CA,*
- *reversible CA,*
- *CA which are nilpotent over periodic configurations.*

PROOF. First, from the point of view of global maps, a geometric transform consists in iterating or composing with bijective maps. So the properties of being surjective or reversible are left unchanged by geometrical transforms. Besides, geometrical transforms map periodic configurations to periodic configurations, cycles of configurations to cycles of configurations (possibly reduced to a single configuration), and attraction basins of such cycles to attraction basins of cycles. Hence, nilpotency over periodic configurations, which is equivalent to the existence of a temporal cycle having all periodic configurations in its attraction basin, is preserved by geometrical transforms. By similar reasoning on the phase space, it is straightforward to check that  $\mathcal{A}$  is nilpotent over periodic configurations if  $\mathcal{B}$  is and  $\mathcal{A} \subseteq \mathcal{B}$  or  $\mathcal{A} \leq \mathcal{B}$ . And  $\mathcal{A} \times \mathcal{B}$  is nilpotent over periodic configurations if both  $\mathcal{A}$  and  $\mathcal{B}$  are. So nilpotency over periodic configurations induces an ideal for  $\preceq$ .

It is also clear that surjectivity and reversibility are preserved by cartesian product. Now suppose  $\mathcal{A} \leq_\pi \mathcal{B}$ . If  $\mathcal{B}$  is surjective then so is  $\mathcal{A}$  since  $G_{\mathcal{A}} \circ \pi = \pi \circ G_{\mathcal{B}}$  and  $\pi$  is by definition surjective. If  $\mathcal{B}$  is reversible, consider any map  $\phi$  such that  $\pi \circ \phi = Id$  and let  $\mathcal{A}_{-1}$  be the CA over state set  $S_{\mathcal{A}}$  and defined by the global map  $G = \pi \circ G_{\mathcal{B}}^{-1} \circ \phi$  (it is a shift-commuting continuous map). Since  $G_{\mathcal{A}} \circ \pi = \pi \circ G_{\mathcal{B}}$ , one can check that  $G_{\mathcal{A}} \circ G = Id$  so  $\mathcal{A}$  is reversible.

Finally, suppose  $\mathcal{A} \subseteq_\iota \mathcal{B}$ . If  $\mathcal{B}$  is reversible then  $\mathcal{A}$  is also reversible since  $\tau \circ G_{\mathcal{A}} = G_{\mathcal{B}} \circ \tau$  and  $\iota$  is by definition injective. If  $\mathcal{B}$  is surjective, then so is  $\mathcal{A}$  because  $\mathcal{B}$  being injective over finite configurations (Moore-Myhill theorem<sup>3</sup>)  $\mathcal{A}$  is also injective over finite configurations ( $\iota$  maps finite configurations to finite configurations). ■

**Theorem 4.4.** *Let  $\mathcal{A}$  and  $\mathcal{B}$  be two reversible CA and  $\preceq$  be a simulation relation among  $\preceq_i$ ,  $\preceq_s$  and  $\preceq_m$ . If  $\mathcal{A} \preceq \mathcal{B}$  then  $\mathcal{A}^{-1} \preceq \mathcal{B}^{-1}$ .*

PROOF. First, it is straightforward to check that the inverse of geometrically transformed instances of  $\mathcal{A}$  are transformed instances of the inverse of  $\mathcal{A}$ . Using what was shown above concerning reversibility, it is thus sufficient to prove the two following properties:

---

<sup>3</sup>In [13], one can find the following theorem: a CA is surjective if and only if there is no pair of finite configurations (*i.e.* uniform except on a finite region) having the same image. The original formulation of the Moore-Myhill theorem [25, 26] supposes the existence of a quiescent state.

- $\mathcal{A} \sqsubseteq_{\iota} \mathcal{B}$  implies  $\mathcal{A}^{-1} \sqsubseteq_{\iota} \mathcal{B}^{-1}$ ,
- $\mathcal{A} \trianglelefteq_g \mathcal{B}$  implies  $\mathcal{A}^{-1} \trianglelefteq_g \mathcal{B}^{-1}$ .

In the first case we have:

$$G_{\mathcal{B}} \circ \bar{\iota} = \bar{\iota} \circ G_{\mathcal{A}} \Rightarrow \bar{\iota} = G_{\mathcal{B}}^{-1} \circ \bar{\iota} \circ G_{\mathcal{A}} \Rightarrow \bar{\iota} \circ G_{\mathcal{A}}^{-1} = G_{\mathcal{B}}^{-1} \circ \bar{\iota}$$

each equality being true on  $S_{\mathcal{A}}^{\mathbb{Z}}$ . In the second case we have:

$$G_{\mathcal{A}} \circ \bar{g} = \bar{g} \circ G_{\mathcal{B}} \Rightarrow G_{\mathcal{A}} \circ \bar{g} \circ G_{\mathcal{B}}^{-1} = \bar{g} \Rightarrow \bar{g} \circ G_{\mathcal{B}}^{-1} = G_{\mathcal{A}}^{-1} \circ \bar{g}$$

each equality being true on  $S_{\mathcal{B}}^{\mathbb{Z}}$ . ■

One immediate consequence of the theorem is that if two reversible CA are equivalent then their inverse CA are also equivalent. What is not obvious however is whether the inverse CA are necessarily in the same class as the initial CA.

**Open Problem 1.** *Consider any simulation relation and  $\sim$  the associated equivalence relation. What are the reversible CA  $F$  such that  $F \sim F^{-1}$ ?*

At the time of writing we have no example of a reversible  $F$  with  $F \not\sim F^{-1}$ .

**Theorem 4.5.** *Let  $\preccurlyeq$  be  $\preccurlyeq_i$  or  $\preccurlyeq_m$ . Then the ideal of reversible CA is principal: there is a reversible CA  $\mathcal{A}$  such that*

$$\mathcal{B} \text{ reversible} \iff \mathcal{B} \preccurlyeq \mathcal{A}.$$

PROOF. In [9], a reversible CA  $\mathcal{B}$  able to simulate any reversible CA is constructed. The notion of simulation used is included in  $\preccurlyeq_i$  and therefore in  $\preccurlyeq_m$ . The implication  $\Rightarrow$  is thus proven and the converse implication is proven by theorem 4.3. ■

For the ideal of surjective CA, the principality is still an open problem in dimension 1.

**Open Problem 2.** *Is the ideal of surjective CA principal, and for which simulation quasi-order?*

Limit sets of CA have received a lot of attention in the literature [6, 15, 11]. The limit set of  $\mathcal{A}$  is the set  $\Omega_{\mathcal{A}}$  of configurations having predecessors arbitrarily far in the past, formally:

$$\Omega_{\mathcal{A}} = \bigcap_t G_{\mathcal{A}}^t(S_{\mathcal{A}}^{\mathbb{Z}}).$$

The next theorem shows that the class of CA with a sofic limit set is nicely captured by  $\preccurlyeq_s$ .

**Theorem 4.6.** *The set of CA with a sofic limit set is an ideal for  $\preccurlyeq_s$ .*

PROOF. For CA of dimension 1, having a sofic limit set is equivalent to having a regular limit language [38]. It is clear that this latter property is left unchanged by geometrical transforms (the limit language is not affected by iterations and shifts, the regularity of the language is not affected by packing). Hence, it is sufficient to show that if  $\mathcal{B}$  has a regular limit language and  $\mathcal{A} \trianglelefteq_g \mathcal{B}$  then  $\mathcal{A}$  also has a regular limit language. Since regular languages are closed under substitution (a classical result which can be found in [14]), it is sufficient to prove that  $\Omega_{\mathcal{A}} = \overline{g}(\Omega_{\mathcal{B}})$ . This last assertion is a direct consequence of  $\mathcal{A} \trianglelefteq_g \mathcal{B}$ , since the following equality holds by recurrence on  $t$ :

$$\overline{g}(G_{\mathcal{B}}^t(S_{\mathcal{B}}^{\mathbb{Z}})) = G_{\mathcal{A}}^t(S_{\mathcal{A}}^{\mathbb{Z}}).$$

■

**Open Problem 3.** Let  $\preceq$  be  $\preceq_i$  or  $\preceq_m$ . Is there a  $\preceq$ -universal CA with a sofic limit set?

#### 4.2.2. Topological dynamics

The properties considered above are purely dynamic: they can be expressed as structural properties of the phase space with the reachability relation only. We now consider properties from topological dynamics: they are expressed with both the reachability relation and the topology (Cantor distance) of the space of configurations. We will show that many of them correspond to ideals of the simulation quasi-orders.

The properties we will consider are derived from the equicontinuity classification of P. K urka [19]. Let  $\mathcal{A}$  be any CA with state set  $Q$  and global rule  $G$  and denote by  $d$  the Cantor distance over  $Q^{\mathbb{Z}}$ .

- $x \in Q^{\mathbb{Z}}$  is an *equicontinuity point* for  $\mathcal{A}$  if

$$\forall \epsilon, \exists \delta, \forall y \in Q^{\mathbb{Z}} : d(x, y) \leq \delta \Rightarrow \forall t, d(G^t(x), G^t(y)) \leq \epsilon.$$

- $\mathcal{A}$  is *sensitive to initial conditions* if

$$\exists \epsilon, \forall \delta, \forall x \in Q^{\mathbb{Z}} \exists y \in Q^{\mathbb{Z}} \exists t : d(x, y) \leq \delta \text{ and } d(G^t(x), G^t(y)) \geq \epsilon.$$

- $\mathcal{A}$  is *(positively) expansive* if

$$\exists \epsilon, \forall x, y \in Q^{\mathbb{Z}} : x = y \iff \forall t, d(G^t(x), G^t(y)) \leq \epsilon.$$

The classification of P. K urka is the following:

$K_1$  is the set of CA for which all configurations are equicontinuity points,

$K_2$  is the set of CA having equicontinuity points,

$K_3$  is the set of CA sensitive to initial conditions,

$K_4$  is the set of expansive CA.

The weakness of this classification is its lack of shift-invariance: the identity and the elementary translation belong to different classes ( $K_1$  and  $K_3$  respectively). Several attempts have been made to overcome this problem by changing the topology [5]. More recently, a new approach has been proposed [32]: the Cantor topology is conserved (with all its good properties) but the topological properties are enriched with a new parameter (a velocity) which is used as the reference direction of information propagation in space-time. The original definitions of P. Kůrka are thus obtained by choosing velocity 0, but now identity and elementary translations are assigned to the same class (with different velocities). This directional dynamic approach is more suitable for our study since, by definition, the equivalence classes of any of our quasi-orders are shift-invariant. We will define 4 classes based on the existence of some direction for which some dynamical behavior is observed.

We say that  $\mathcal{A}$  is a *rescaling* of  $\mathcal{B}$  if there are transforms  $\alpha$  and  $\beta$  such that  $\mathcal{A}^{(\alpha)} \equiv \mathcal{B}^{(\beta)}$ . We then consider the following 4 classes:

- the set  $\mathcal{T}_1$  of CA which are a rescaling of some equicontinuous CA,
- the set  $\mathcal{T}_2$  of CA which are a rescaling of some CA having equicontinuity points,
- the set  $\mathcal{T}_3$  of CA which are not in  $\mathcal{T}_2$ , *i.e.* CA which are sensitive in every directions<sup>4</sup>,
- the set  $\mathcal{T}_4$  of CA which are a rescaling of some (positively) expansive CA.

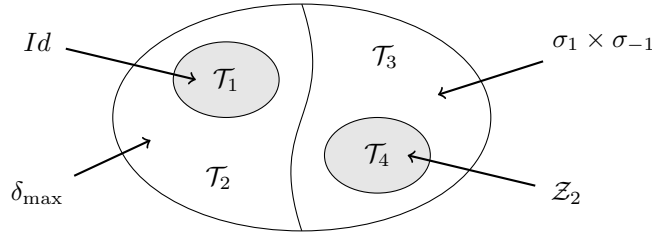


Figure 2: Four kinds of topological dynamics.

Figure 2 is justified by the following theorem.

**Theorem 4.7.** *We have the following inclusions:*

1.  $\mathcal{T}_1 \subseteq \mathcal{T}_2$ ,
2.  $\mathcal{T}_4 \subseteq \mathcal{T}_3$ .

Moreover, each of the sets  $\mathcal{T}_1$ ,  $\mathcal{T}_2 \setminus \mathcal{T}_1$ ,  $\mathcal{T}_3 \setminus \mathcal{T}_4$  and  $\mathcal{T}_4$  is non-empty.

PROOF. The first inclusion follows from definitions. The second follows from proposition 3.2 of [32] which asserts that the set of directions with equicontinuity points and the set of expansive directions cannot be simultaneously empty.

<sup>4</sup>For one-dimensional CA, the set of sensitive CA is the complement of the set of CA having equicontinuity points (see [19]). In [32], this complementarity is shown for any direction.

Non-emptiness of  $\mathcal{T}_1$  and  $\mathcal{T}_4$  follows from the existence of equicontinuous (e.g. the identity) and (positively) expansive CA (e.g.  $\mathcal{Z}_2$ ). Moreover, any CA having an equicontinuity point which is not equicontinuous (e.g. the CA of local rule  $\delta_{\max}(a, b, c) = \max(a, b, c)$ ) cannot be in  $\mathcal{T}_1$  (equicontinuity is preserved by rescaling), so it is in  $\mathcal{T}_2 \setminus \mathcal{T}_1$ . Finally,  $\sigma_1 \times \sigma_{-1} \in \mathcal{T}_3 \setminus \mathcal{T}_4$ . Indeed, for  $\sigma \times \sigma^{-1}$ , any direction is either a direction of right-expansivity or a direction of left-expansivity, neither both. So  $\sigma \times \sigma^{-1} \notin \mathcal{T}_4$ . Finally,  $\sigma \times \sigma^{-1} \notin \mathcal{T}_2$  since, by proposition 3.2 of [32], no direction of (left or right) expansivity can be a direction with equicontinuity points. ■

**Theorem 4.8.**

1.  $\mathcal{T}_1$  is an ideal for any simulation  $\preceq$  among  $\preceq_s$ ,  $\preceq_i$  and  $\preceq_m$ ;
2.  $\mathcal{T}_2$  is an ideal for  $\preceq_s$ ;
3.  $\mathcal{T}_4$  is an ideal for  $\preceq_i$ .

PROOF. First, consider any  $\mathcal{A}, \mathcal{B} \in \mathcal{T}_1$ . Then there are CA  $\mathcal{A}'$  and  $\mathcal{B}'$  which are both equicontinuous and  $\preceq$ -equivalent to  $\mathcal{A}$  and  $\mathcal{B}$  respectively. Then, if  $\mathcal{C} = \mathcal{A}' \times \mathcal{B}'$  we have  $\mathcal{C} \in \mathcal{T}_1$  and by theorem 2.3 we have both  $\mathcal{A} \preceq \mathcal{C}$  and  $\mathcal{B} \preceq \mathcal{C}$ . The same reasoning can be applied to  $\mathcal{T}_4$  and  $\mathcal{T}_2$ . Thus we have shown the second condition of the definition of ideals for the three properties considered here.

To conclude the theorem, and since the three properties considered are by definition invariant by rescaling, it is sufficient to prove:

- if  $\mathcal{A} \sqsubseteq \mathcal{B}$  or  $\mathcal{A} \trianglelefteq \mathcal{B}$  then  $\mathcal{B}$  equicontinuous  $\Rightarrow \mathcal{A}$  equicontinuous;
- if  $\mathcal{A} \trianglelefteq \mathcal{B}$  then  $\mathcal{B}$  has equicontinuous points  $\Rightarrow \mathcal{A}$  has equicontinuous points;
- if  $\mathcal{A} \sqsubseteq \mathcal{B}$  then  $\mathcal{B}$  expansive  $\Rightarrow \mathcal{A}$  expansive.

The first assertion follows from the characterisation of equicontinuous CA as ultimately periodic CA [19].

For the second assertion, if  $\mathcal{A} \trianglelefteq_\pi \mathcal{B}$  then for all  $x, y \in S_B^{\mathbb{Z}}$  we have the inequality  $d(\pi(x), \pi(y)) \leq d(x, y)$ . Moreover, for any  $y_1 \in S_A^{\mathbb{Z}}$  there is some  $y_2 \in S_B^{\mathbb{Z}}$  such that  $\pi(y_2) = y_1$  and  $d(\pi(x), y_1) = d(x, y_2)$  (choose  $y_2$  so that it equals  $x$  on the cells around position 0). Hence, if  $x$  is an equicontinuous point for  $\mathcal{B}$  then  $\pi(x)$  is an equicontinuous point for  $\mathcal{A}$ .

Finally, for the third assertion, it is sufficient to notice that the property of expansivity is defined by a formula using only universal quantifications on configurations so it remains true on a subset of configurations. ■

$\mathcal{T}_2$  is not an ideal for  $\preceq_i$  and neither for  $\preceq_m$  as shown by the following example.

**Example 4.1.** Consider  $\mathcal{B} \in \mathcal{T}_3$  of radius 1 and let  $\mathcal{A}$  be the CA with radius 1, states set  $S_A = S_B \cup \{M\}$  (with  $M \notin S_B$ ) with local rule  $f_A$  defined by

$$f_A(x, y, z) = \begin{cases} f_B(x, y, z) & \text{if } \{x, y, z\} \subseteq S_B, \\ y & \text{else.} \end{cases}$$

$\mathcal{B} \sqsubseteq \mathcal{A}$  so  $\mathcal{B} \preceq_i \mathcal{A}$ . However  $\mathcal{A} \in \mathcal{T}_2$  since the configuration  ${}^\omega M {}^\omega$  is an equicontinuous point. ■

Notice also that  $\mathcal{T}_3$  cannot be an ideal because  $\sigma_1 \times \sigma_{-1} \in \mathcal{T}_3$  simulates  $\sigma \in \mathcal{T}_1$ .

**Open Problem 4.** *Are there  $\mathcal{A} \notin \mathcal{T}_4$  and  $\mathcal{B} \in \mathcal{T}_4$  such that  $\mathcal{A} \preceq_s \mathcal{B}$  (i.e. the simulator CA is expansive up to rescaling but the simulated CA is not expansive, even up to rescaling)?*

#### 4.3. (Un)decidability

The fact that many properties related to the simulation quasi-orders are undecidable is no surprise. For instance the nilpotency property, which is an undecidable problem [18], corresponds to an equivalence class in the three quasi-orders (theorem 3.1). However, there are non-trivial properties of these quasi-orders which are decidable (see below) and the edge between decidable and undecidable properties is hard to catch.

In this section, we consider two kinds of problems in simulation quasi-orders: lower bounds (being above some fixed CA or set of CA) and upper bounds (being simulated by some fixed CA or some CA from a fixed set).

**Theorem 4.9 ([23]).** *The set of CA of radius 1 with a spreading state and nilpotent over periodic configurations is not co-recursively enumerable.*

**Theorem 4.10.** *Let  $\mathcal{A}$  be any CA which is not nilpotent over periodic configurations. Let  $\preceq$  be either  $\preceq_i$  or  $\preceq_m$ . Then the set of CA  $\mathcal{B}$  such that  $\mathcal{A} \preceq \mathcal{B}$  is not co-recursively enumerable.*

PROOF. We describe a computable transformation which, given a CA  $\mathcal{C}$  of radius 1 with a spreading state, produces a CA  $\mathcal{B}$  with the following properties:

- if  $\mathcal{C}$  is not nilpotent over periodic configurations then  $\mathcal{A} \preceq \mathcal{B}$ ;
- if  $\mathcal{C}$  is nilpotent over periodic configurations then so is  $\mathcal{B}$ .

The theorem follows by theorem 4.3 since we have reduced the problem ' $\mathcal{A} \preceq \mathcal{B}$ ' to the problem of nilpotency over periodic configurations (reduced to CA of radius 1 with a spreading state).

We now describe the construction of  $\mathcal{B}$  from  $\mathcal{C}$ . Suppose  $\mathcal{C}$  has a spreading state  $q$ .  $\mathcal{B}$  is the CA of radius 1 and states set  $S_{\mathcal{B}} = (S_{\mathcal{C}} \setminus \{q\}) \times S_{\mathcal{A}} \cup \{q\}$  with local rule  $f_{\mathcal{B}}$  defined by:

$$f_{\mathcal{B}}(a, b, c) = \begin{cases} (f_{\mathcal{C}}(a_1, b_1, c_1), f_{\mathcal{A}}(a_2, b_2, c_2)) & \text{if } \begin{cases} a, b, c \in S_{\mathcal{B}} \setminus \{q\} \text{ and} \\ f_{\mathcal{C}}(a_1, b_1, c_1) \neq q, \end{cases} \\ q & \text{in any other case,} \end{cases}$$

where  $a_i, b_i$  and  $c_i$  represent component  $i$  of  $a, b$  and  $c$ . Any periodic configuration  $c$  of  $\mathcal{B}$  either leads to the uniform configuration  $\bar{q}$ , or contains a periodic configuration of  $\mathcal{C}$  in its first component. Hence, if  $\mathcal{C}$  is nilpotent over periodic configurations, then so is  $\mathcal{B}$  (because  $q$  is precisely the spreading state of  $\mathcal{C}$ ). If  $\mathcal{C}$  is not nilpotent over periodic configurations, then there is a word  $u \in (S_{\mathcal{C}} \setminus \{q\})^m$  and an integer  $t \geq 1$  such that the periodic configuration  $c$  of period  $u$  verifies  $G_{\mathcal{C}}^t(c) = c$ . Therefore, by definition of  $\mathcal{B}$ , we have  $\mathcal{A}^{(m,1,t,0)} \sqsubseteq_i \mathcal{B}^{(m,1,t,0)}$  where  $i : S_{\mathcal{A}}^m \rightarrow S_{\mathcal{B}}$  is defined by:

$$i(a_1, a_2, \dots, a_m) = ((a_1, u_1), \dots, (a_m, u_m)).$$

■

This result shows that it is generally undecidable to know whether a CA is lower-bounded by a given (fixed) one. However, there are noticeable exceptions in one dimension for  $\preceq_s$  and  $\preceq_m$ .

**Theorem 4.11.** *Let  $\preceq$  be either  $\preceq_s$  or  $\preceq_m$  and let  $\mathcal{A}$  be a nilpotent CA. Then the problem of determining if a given  $\mathcal{B}$  is above  $\mathcal{A}$  for  $\preceq$  is decidable.*

PROOF. We are going to show that  $\mathcal{A} \preceq \mathcal{B}$  if and only if  $\mathcal{B}$  is not surjective and the theorem follows by decidability of surjectivity in one dimension [1]. First, by theorem 4.3, if  $\mathcal{B}$  is surjective then  $\mathcal{A} \not\preceq \mathcal{B}$ . Suppose now that  $\mathcal{B}$  is not surjective, *i.e.* that  $\mathcal{B}$  possesses some Eden word  $u \in S_{\mathcal{B}}^m$  for some length  $m$ . Then, denoting by  $\mathcal{C}$  the CA over states set  $S_{\mathcal{C}} = \{0, 1\}$  which is constant equal to 0, we have  $\mathcal{C} \trianglelefteq_{\pi} \mathcal{B}^{(m,1,1,0)}$  if  $\pi : S_{\mathcal{B}}^m \rightarrow S_{\mathcal{A}}$  verifies  $\pi(w) = 0$  if and only if  $w = u$ . We deduce by theorem 3.1 that  $\mathcal{A} \preceq \mathcal{B}$ . ■

**Open Problem 5.** *Is there a non-surjective CA  $\mathcal{A}$  which cannot injectively simulate any nilpotent CA? Is the problem of being above the class of nilpotent CA for injective simulation a decidable problem?*

Concerning upper-bound problems, the edge between decidability and undecidability is also non-trivial. For instance, theorem 4.5 shows the existence of a CA  $\mathcal{A}$  such that the upper-bound decision problem ' $\mathcal{B} \preceq \mathcal{A}$ ?' is decidable in dimension 1.

## 5. Tops of the Orders

In this section we study maximal elements of the quasi-orders. These CA are able to simulate any other CA

**Definition 5.1.** *Let  $\preceq$  be any relation among  $\preceq_i$ ,  $\preceq_s$  and  $\preceq_m$ . A CA  $\mathcal{A}$  is said  $\preceq$ -universal if for any  $\mathcal{B}$  we have  $\mathcal{B} \preceq \mathcal{A}$ . It is strongly  $\preceq$ -universal if it strongly  $\preceq$ -simulates any other CA.*

The notion of strong  $\preceq_i$ -universality above is exactly the same notion as *intrinsic universality* defined in section 5 of [8] and has already been considered several times in the literature (see [31] for a survey). In fact, strong and general universality are the same notion for  $\preceq_i$  and  $\preceq_m$ .

**Theorem 5.1.** *There exist strongly  $\preceq_i$ -universal CA and all  $\preceq_i$ -universal CA are strongly  $\preceq_i$ -universal. The same is true for  $\preceq_m$ .*

PROOF. For the existence of strongly  $\preceq_i$ -universal CA, see [31]. The theorem follows by application of theorem 12 of [8]. ■

Of course, any  $\preceq_i$ -universal is also  $\preceq_m$ -universal. The converse is an open problem.

**Open Problem 6.** *Do the notions of  $\preceq_i$ -universality and  $\preceq_m$ -universality coincide?*

Concerning  $\preceq_s$ , the situation is different: no CA is strongly  $\preceq_s$ -universal<sup>5</sup>.

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<sup>5</sup>The proof of this fact was suggested by G. Richard.

**Theorem 5.2.** *There is no strongly  $\preceq_s$ -universal CA.*

PROOF. Suppose for the sake of contradiction that there is some strongly  $\preceq_s$ -universal  $\mathcal{A}$ . Consider a uniform configuration  $c$  of  $\mathcal{A}$ . There is  $n$  such that the orbit of  $c$  under  $\mathcal{A}$  contains  $n$  different configurations (the orbit is ultimately periodic). Now consider  $\mathcal{B}$  with  $n + 1$  states such that its uniform configurations are all in the same cycle of length  $n + 1$ . By hypothesis, for any  $\mathcal{B}$  there is some geometric transform  $\alpha$  such that  $\mathcal{B} \preceq_s \mathcal{A}^{(\alpha)}$ . Let  $d$  be the corresponding configuration of  $c$  for  $\mathcal{A}^{(\alpha)}$ . The orbit of  $d$  contains at most  $n$  different configurations and it is therefore the same for the orbit of  $s(d)$  under  $\mathcal{B}$ . But  $s(d)$  is necessarily uniform and we get a contradiction with the choice of  $\mathcal{B}$ . ■

The theorem 12 of [8] don't apply for  $\preceq_s$ . However, we are not able either to construct a  $\preceq_s$ -universal CA, nor to prove that there is none.

**Open Problem 7.** *Is there a  $\preceq_s$ -universal CA?*

For the rest of this section, we consider only  $\preceq_i$  and  $\preceq_m$ .

### 5.1. On the Way to the Top

Universal CA are not hard to construct and the property of being universal is recursively enumerable since simulation relations considered here are recursively enumerable. However universality is not co-recursively enumerable as shown by the following theorem. The case of  $\preceq_i$ -universality was proven in [30]. Using theorem 4.10, the proof below is direct and includes the case of  $\preceq_m$ .

**Theorem 5.3.** *The set of  $\preceq_i$ -universal CA is not co-recursively enumerable and neither is the set of  $\preceq_m$ -universal CA.*

PROOF. There exists a CA which is  $\preceq_i$ -universal but not nilpotent over periodic configurations. To see this consider any universal CA and add a new state which is spreading: the resulting CA, say  $\mathcal{A}$ , contains at least two disjoint periodic orbits of periodic configurations and is thus not nilpotent over periodic configurations. The theorem follows by application of theorem 4.10 to  $\mathcal{A}$  since  $\mathcal{A}$  is by construction both  $\preceq_i$ -universal and  $\preceq_m$ -universal. ■

This result has some consequences on the structure of simulation quasi-orders 'near' the top. The following theorem shows that a non-universal CA is always 'infinitely far' from the class of universal ones.

**Theorem 5.4.** *Let  $\preceq$  be  $\preceq_i$  or  $\preceq_m$ . And let  $\mathfrak{U}$  be the set of  $\preceq$ -universal CA. Then we have:*

1.  $\mathcal{A} \times \mathcal{B} \in \mathfrak{U} \iff \mathcal{A} \in \mathfrak{U} \text{ or } \mathcal{B} \in \mathfrak{U}$ ,
2. *if  $\mathcal{A} \notin \mathfrak{U}$  then there is  $\mathcal{B} \notin \mathfrak{U}$  with  $\mathcal{A} \preceq \mathcal{B}$  but  $\mathcal{B} \not\preceq \mathcal{A}$ .*

PROOF.

1. By theorem 2.3 we have  $\mathcal{A} \preceq \mathcal{A} \times \mathcal{B}$  and  $\mathcal{B} \preceq \mathcal{A} \times \mathcal{B}$  which proves one direction. Moreover, there exists  $\mathcal{C} \in \mathfrak{U}$  with 2 states only [2, 28]. If we suppose  $\mathcal{A} \times \mathcal{B} \in \mathfrak{U}$  then, by theorem 5.1, it strongly simulates  $\mathcal{C}$ . Hence, by theorem 4.1, we have either  $\mathcal{C} \preceq \mathcal{A}$  or  $\mathcal{C} \preceq \mathcal{B}$  and thus either  $\mathcal{A} \in \mathfrak{U}$  or  $\mathcal{B} \in \mathfrak{U}$ .
2. Let  $\mathcal{A} \notin \mathfrak{U}$ . If  $\mathcal{A}$  was such that  $\mathcal{C} \preceq \mathcal{A}$  for all  $\mathcal{C} \notin \mathfrak{U}$  then the complement of  $\mathfrak{U}$  would be the set  $\{\mathcal{C} : \mathcal{C} \preceq \mathcal{A}\}$  and  $\mathfrak{U}$  would be co-recursively enumerable contradicting theorem 5.3. So there is  $\mathcal{C} \notin \mathfrak{U}$  with  $\mathcal{C} \not\preceq \mathcal{A}$ . To conclude the proof it is sufficient to choose  $\mathcal{B} = \mathcal{A} \times \mathcal{C}$  (theorem 2.3). ■



### 5.2. Necessary But Not Sufficient Conditions

The purpose of this section is twofold. It compares the notions of universality defined above to other definitions of the literature and, by doing this, presents tools and techniques to prove non-universality of some CA (other proofs of non-universality for other purposes are developed in section 6).

One of the techniques we use to ensure that some CA is not universal yet achieving some behavior  $B$ , is to add a spreading state and let the CA generates this state if it detects somewhere that the current configuration doesn't correspond to a 'legal' configuration, *i.e.* a configuration occurring normally when producing the behavior  $B$ . Proofs of non-universality with this technique rely on the lemma below. Before stating and proving the lemma, we need to give some precisions on spreading states and sets of configurations 'supporting' a simulation.

First, the notion of spreading state is sensitive to the choice of the syntactical representation of the CA because it depends on the choice of the neighborhood. In the sequel we say a CA  $\mathcal{A}$  has a spreading state  $\kappa$  if any cell changes to state  $\kappa$  when  $\kappa$  appears in its minimal neighborhood (*i.e.* the minimal set of cells upon which the local rule effectively depends).

Second, given a relation of the form  $\mathcal{A} \sqsubseteq_i \mathcal{B}^{(m,1,t,z)}$ , there is an isomorphism between  $(\mathcal{A}, S_{\mathcal{A}}^{\mathbb{Z}})$  and  $(\mathcal{B}^{(m,1,t,z)}, (i(S_{\mathcal{A}}))^{\mathbb{Z}})$  as dynamical systems. At the level of  $\mathcal{B}$ , the configurations involved in this relation is the set  $X$  of configurations made of infinite concatenation of elements of  $i(S_{\mathcal{A}}) \subseteq S_{\mathcal{B}}^m$  (viewed as words of length  $m$  over alphabet  $S_{\mathcal{B}}$ ). This kind of sets are called *block-subshifts* and discussed in more details in section 3.2 of [8]. In the sequel, such a set  $X$  is called the *support* of the simulation.

**Lemma 5.1.** *Let  $\mathcal{A}$  be a CA without spreading state and  $\mathcal{B}$  be a CA with a spreading state  $\kappa$ . If  $\mathcal{B}$  strongly  $\preceq_m$ -simulates  $\mathcal{A}$ , then the support  $X$  of the simulation cannot contain  $\kappa$ .*

PROOF. By hypothesis, there are parameters  $m, t, \tau, z$  and a CA  $\mathcal{C}$  such that

$$\mathcal{A} \preceq_{\pi} \mathcal{C} \sqsubseteq_i \mathcal{B}^{(m,\tau,t,z)}.$$

By choice of  $\mathcal{B}$ ,  $\mathcal{B}^{(m,\tau,t)}$  admits  $\kappa^m$  as spreading state. Moreover, by definition of  $\preceq$ , the minimal neighborhood of  $\mathcal{A}$  is included in the minimal neighborhood of  $\mathcal{B}^{(m,\tau,t)}$ . Thus, if  $\kappa$  appears in some configuration of  $X$  then the state  $\pi(i^{-1}(\kappa^m))$  is a spreading state for  $\mathcal{A}$  because  $\kappa^n$  also appears in  $X$  for arbitrarily large  $n$ . ■

We first study how embeddings of Turing machines into CA can relate the notions of universality for Turing machines to the notions of universality derived from quasi-orders as defined above.

An embedding of a Turing machine  $\mathcal{M}$  into a CA  $\mathcal{A}$  is an embedding of the instantaneous descriptions of  $\mathcal{M}$  into configurations of  $\mathcal{A}$  such that instantaneous descriptions of successive steps of  $\mathcal{M}$  corresponds to successive steps of  $\mathcal{A}$  via the embedding. We don't give any formal definition of embedding since we will never prove negative results (*i.e.* assertions of the form 'there is no embedding of  $\mathcal{M}$  such that...'). However, the embeddings we use in the sequel are classical and already appeared in the literature (see [34]).

**Theorem 5.5.** *For any Turing machine  $\mathcal{M}$ , there exists a CA  $\mathcal{A}$  which embeds  $\mathcal{M}$  but is not  $\preceq_m$ -universal.*

PROOF. Let  $\mathcal{M} = (S_{\mathcal{M}}, Q_{\mathcal{M}}, \phi_{\mathcal{M}})$  where  $S_{\mathcal{M}}$  is the set of states of  $\mathcal{M}$ ,  $Q_{\mathcal{M}}$  is the tape alphabet, and

$$\phi_{\mathcal{M}} : S_{\mathcal{M}} \times Q_{\mathcal{M}} \rightarrow S_{\mathcal{M}} \times Q_{\mathcal{M}} \times \{-1, 0, 1\}$$

is the transition function of  $\mathcal{M}$ . We construct a CA  $\mathcal{A}$  over state set

$$S_{\mathcal{A}} = Q_{\mathcal{M}} \times \{\leftarrow, \rightarrow\} \cup Q_{\mathcal{M}} \times S_{\mathcal{M}} \cup \{\kappa\}$$

where  $\rightarrow$  and  $\leftarrow$  are states not already in  $S_{\mathcal{M}}$ . Each cell of  $\mathcal{A}$  corresponds to a tape position of  $\mathcal{M}$ : it contains a letter from the tape alphabet and either a head with its current state or no head but an indication  $\leftarrow$  or  $\rightarrow$  telling in which direction to find the head. On configurations containing a single head,  $\mathcal{A}$  mimics transitions of  $\mathcal{M}$  step by step as expected. Thus,  $\mathcal{A}$  embeds  $\mathcal{M}$ . In addition,  $\mathcal{A}$  checks that  $\leftarrow$  never occur to the left of a state from  $S_{\mathcal{M}}$  or a  $\rightarrow$  (and symmetrically for  $\rightarrow$ ). If the check fails, then the state  $\kappa$  is generated and spreads.

This construction ensures that, for any initial configuration  $c$ , if the orbit of  $c$  never contains an occurrence of  $\kappa$  then it contains at most one head. Hence, these orbits are such that at any time step state changes occur on the neighborhood of at most one position (a head move involves a state change in two adjacent cells).

Now suppose that  $\mathcal{A}$  is  $\preceq_m$ -universal and consider the CA  $\mathcal{B} = \sigma_1 \times \sigma_{-1}$ .  $\mathcal{A}$  strongly simulates  $\mathcal{B}$  (theorem 5.1). Since  $\mathcal{B}$  has no spreading state, then the set  $X$  of configurations of  $\mathcal{A}$  on which the simulation occurs never contains  $\kappa$ . We deduce that all orbits of configurations from  $X$  have the property described above. This implied that  $\mathcal{B}$  is such that on all its orbits, at most two cells change their states between two steps: this in contradiction with the choice of  $\mathcal{B}$ . ■

Turing-universality of cellular automata is a fairly vague notion in the literature. We don't give a formal definition here since we won't prove any negative result concerning Turing-universality. We just consider that a CA able to embed a universal Turing machine<sup>6</sup> is Turing-universal.

We can choose  $\mathcal{M}$  to be universal in the previous theorem (theorem 5.5). In this case, since the embedding used in the proof ensures that  $\mathcal{M}$  is simulated in real time by  $\mathcal{A}$ , we deduce that the following problem is P-complete:

**Input:** a state  $q \in S_{\mathcal{A}}$ , an integer  $t \geq 1$ , and a word  $u \in S_{\mathcal{A}}^{2rt+1}$  where  $r$  is the radius of  $\mathcal{A}$ ;

**Query:** do we have  $\mathcal{A}^t(u) = q$ ?

This problem of finite triangle computation has been considered several times in the literature and it has been proven that it was P-complete for particular CA [12, 27]. This notion of complexity inherited from sequential computation theory fails to capture the notion of universality associated to simulation quasi-orders.

**Corollary 5.1.** *There exists a CA which is Turing-universal and P-complete but not  $\preceq_m$ -universal.*

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<sup>6</sup>We don't give any formal notion of universality for Turing machine either. In fact, we only need to suppose the existence of at least one universal Turing machine.

## 6. Induced Orders

This section aims at studying particular CA or sets of CA for the ordered structure they induce in the simulation quasi-orders. While studying various properties of the quasi-orders in the previous sections, we have already established the existence of several induced infinite structures.

For instance, theorem 5.4 allows to construct an infinite strictly increasing chain of non-universal CA starting from any non-universal CA for the quasi-orders associated to  $\preceq_i$  and  $\preceq_m$ . Besides, theorem 3.4 implies the existence of infinite chains in the three quasi-orders studied in this paper.

Section 6.1 below gives a way to construct chains of length  $\omega + \omega$  and an hint about the existence of chains of length  $\omega \times \omega$ . However, we leave open the question of the longest chain induced in any of the quasi-orders. We don't even know if one of them admits a dense chain.

**Open Problem 8.** *Does one of the quasi-orders admit a dense induced order?*

### 6.1. Limit Cartesian Product

We have seen in theorem 5.4 that if  $\mathcal{A}$  is not universal, then  $\mathcal{A} \times \mathcal{A}$  cannot be universal. Therefore, no finite Cartesian product of  $\mathcal{A}$  with itself can be universal. Therefore, we have a chain of non-universal CA:

$$\mathcal{A} \preceq \mathcal{A} \times \mathcal{A} \preceq \mathcal{A} \times \mathcal{A} \times \mathcal{A} \preceq \dots$$

For some  $\mathcal{A}$ , the chain collapses in a single equivalence class, *e.g.* if  $\mathcal{A}$  is a translation (see lemma 3.4). However, the following theorem shows that for some  $\mathcal{A}$ , the chain is strictly increasing. Moreover,  $\mathcal{A}$  can be chosen so that it embeds any Turing machine.

**Theorem 6.1.** *For any Turing machine  $\mathcal{M}$ , there is a CA  $\mathcal{A}$  which embeds  $\mathcal{M}$  and such that for any  $1 \leq n < m$ , one has:*

$$\underbrace{\mathcal{A} \times \dots \times \mathcal{A}}_m \not\preceq_m \underbrace{\mathcal{A} \times \dots \times \mathcal{A}}_n.$$

PROOF. Let  $\mathcal{A}$  be the CA constructed in the proof of theorem 5.5. We can suppose that  $\mathcal{M}$  is such that it can produce infinite sequences of left move of its head when started from a special state (not the initial state) over a blank tape, and more precisely that the sequence of moves leaves the tape blank. If  $\mathcal{M}$  does not have this property, just add some states to achieve this behavior. We can suppose the same for right moves.

Denote by  $\mathcal{B}_m$  the product of  $m$  copies of  $\mathcal{A}$  and by  $\mathcal{B}_n$  the product of  $n$  copies. Suppose for the sake of contradiction that  $\mathcal{B}_m \preceq_m \mathcal{B}_n$ . We can construct for any set of positions  $z_1, \dots, z_m$  a configuration  $c$  of  $\mathcal{B}_m$  such that for all  $i$  the  $i$ th component contains a correct instantaneous description of  $\mathcal{M}$  where the head is at position  $z_i$  in a state suitable to generate an infinite sequence of left or right moves (as supposed above). Now let  $c'$  be a configuration of  $\mathcal{B}_n$  corresponding to  $c$  via simulation. First, if some component  $i$  of  $c'$  contains a spreading state, it will spread and, after some time  $t$ , will be present at some position where the configuration  $G_{\mathcal{B}_m}^t(c)$  contains no head, but only a blank tape symbol on each component. This means that blocks of blank tape symbols

in  $\mathcal{B}_m$  can be simulated by blocks of  $\mathcal{B}_n$  where the  $i$ th component is a block of spreading states. Considering again the orbit of  $c$ , we deduce that it can be simulated by a configuration  $c''$  where the  $i$ th component is everywhere a spreading state except at a finite number of positions. Thus after some time, the  $i$ th component will become uniform and constant. It is then straightforward to show that it is useless for the simulation and that in fact  $\mathcal{B}_m$  on  $c$  can be simulated by only  $n - 1$  copies of  $\mathcal{A}$ .

Applying the reasoning inductively, we can therefore suppose that no spreading state appears on any component in the orbit of the configuration  $c'$  defined above. Since, the orbit of  $c$  is such that there are  $m$  distant positions where some states change at each step, it must be the case in the orbit of  $c'$ . Since,  $n < m$ , there must be some component with two heads and therefore a spreading state must appear after the first step: this is in contradiction with what we have just supposed. ■

For the CA  $\mathcal{A}$  of the previous theorem, we can ask if the infinite chain of Cartesian products is upper-bounded by some non-universal CA, or if any CA able to simulate each product of the chain is necessarily universal. One can imagine that for a sufficiently simple  $\mathcal{A}$ , there is some room above the chain of products of  $\mathcal{A}$  and below the class of universal CA.

The rest of this section is devoted to the proof of a stronger result: for any  $\mathcal{A}$ , there is a CA  $\mathcal{B}$  which is able to simulate any finite product of  $\mathcal{A}$  and such that  $\mathcal{B}$  is universal if and only if  $\mathcal{A}$  is universal. Moreover,  $\mathcal{B}$  can be obtained from  $\mathcal{A}$  constructively. Because it extends property of Cartesian product given by theorem 5.4, this construction will be called *limit product* in the sequel. If  $\mathcal{A}$  is a CA, its limit product is denoted by  $\mathcal{A}_\infty$ .

*Note:* In the rest of this section we only consider the simulation  $\preceq_m$ .

Without loss of generality, we can suppose that  $\mathcal{A}$  has radius 1 (theorem 2.3). To be able to simulate the product  $\mathcal{B}$  of  $n$  copies of  $\mathcal{A}$ ,  $\mathcal{A}_\infty$  is made of three layers (its state set is a Cartesian product union a single state, which is a spreading state as explain hereafter):

1. the *state* layer,
2. the *transport* layer, and
3. the *synchronisation* layer.

It proceeds as follows.

**State layer.** Each component of a cell of  $\mathcal{B}$  is simulated by a block of three adjacent cells in the state layer of  $\mathcal{A}_\infty$ . More precisely, component  $i$  ( $0 \leq i \leq n - 1$ ) of cell  $z$  of  $\mathcal{B}$  is simulated by the block of three cells of  $\mathcal{A}_\infty$  beginning at position  $3(nz + i)$ . This block is referred to as  $B_{z,i}$  in the sequel. In  $B_{z,i}$ , the center cell stores the  $i$ th component of the cell  $z$  of  $\mathcal{B}$  and the two other are used to store temporarily the  $i$ th components of cell  $z - 1$  and  $z + 1$ .

**Transport layer.** The role of the transport layer is precisely to bring states of  $i$ th components corresponding to cell  $z - 1$  and  $z + 1$  of  $\mathcal{A}$  to the dedicated cells of  $\mathcal{A}_\infty$  in  $B_{z,i}$ . Then, the transition  $f_{\mathcal{A}}(x_{z-1}, x_z, x_{z+1})$  of the  $i$ th component of  $\mathcal{B}$  can be simulated locally by  $\mathcal{A}_\infty$  in  $B_{z,i}$ . Transport is done in parallel for any  $i$  and any  $z$ . To do this, the transport layer is made of a succession of particles (one every three cells), each one being able to

carry a state of  $\mathcal{A}$ . Initially aligned with the center of blocks, the particles move in parallel according to a cycle of five steps:

1. move right by  $3n$  cells and read the state seen on the state layer;
2. move left by  $3n - 1$  cells and write the memorized state on the state layer;
3. move left by  $3n + 1$  cells and read the state seen on the state layer;
4. move left by  $3n - 1$  cells and write the memorized state on the state layer;
5. move 1 cell right and apply local rule  $f_{\mathcal{A}}$  on state layer at the current position;

**Synchronisation layer.** The role of the synchronisation layer is to orchestrate the cycle of particle moves and it must be able to do it for arbitrary large values of  $n$  (simulating arbitrarily large Cartesian products of  $\mathcal{A}$  is sufficient to simulate all products of  $\mathcal{A}$ ). It contains a flag that can take one of the four indications 'left', 'right', 'read', 'write' and 'transition'. The flag is changed everywhere synchronously according to a cycle suitable to ensure that particles of the transport layer produce the cycle described above when they follow the instruction given by the flag.

We now describe in detail the synchronisation layer. Denote by  $u_n$  the flag sequence mentioned above in the simulation of a product of  $n$  copies of  $\mathcal{A}$ , and let  $E$  be the set of flag states.

**Theorem 6.2.** *There is a CA  $\mathcal{C}$  with a spreading state  $\kappa$  and a map  $\pi : S_{\mathcal{C}} \rightarrow E$  such that  $\mathcal{C}$  is not  $\preceq_m$ -universal, and, for any configuration  $c \in S_{\mathcal{C}}^{\mathbb{Z}}$ , one of the following property is true:*

**Cycle:** *at each time in the orbit of  $c$ , all cells have the same image by  $\pi$  and the sequence with time of this common image is periodic of period  $u_n$  for some  $n$ ;*

**Frozen:** *at each time in the orbit of  $c$ , all cells have the same image by  $\pi$ , but this common image remains constant after a certain time;*

**Error:** *the spreading state appears at some time in the orbit of  $c$ .*

*Moreover  $\mathcal{C}$  is such that there are configurations having the 'cycle' property above producing period  $u_n$  for arbitrarily large  $n$ .*

PROOF. First, notice that flag changes in the sequence  $u_n$  are separated by a number of steps which is either constant (independant of  $n$ ), or of the form  $3n + c$  with  $c$  a constant (we can suppose  $c \geq 0$  without loss of generality). To simplify notations, we will suppose in this proof that  $u_n$  alternates between two values 0 and 1 every  $3n$  steps. Adapting the proof for the real  $u_n$  is just a matter of adding a finite set of special states to deal with constants.

The proof is based on a reversible solution  $\mathcal{B}$  to the firing squad synchronization problem proposed by K. Imai and K. Morita: in [16], they construct a

reversible CA  $\mathcal{B}$  with a subset of states  $F$  (the firing states) such that for any  $n$ , there is a periodic configuration  $c_n$  verifying<sup>7</sup>:

- $G_{\mathcal{B}}^{3n}(c_n) \in F^{\mathbb{Z}}$
- $G_{\mathcal{B}}^t(c_n) \in (S_{\mathcal{B}} \setminus F)^{\mathbb{Z}}$  for all  $t$ ,  $0 \leq t < 3n$ .

Without loss of generality, we can suppose that  $\mathcal{B}$  and its inverse are syntactically represented with the same radius. We now define a CA  $\mathcal{C}_0$  of radius  $r$ , with states set  $S_{\mathcal{C}_0} = S_{\mathcal{B}} \times S_{\mathcal{B}} \times \{0, 1\}$ , and with transition function:

$$f_{\mathcal{C}_0}((a_{-r}, a'_{-r}, b_{-r}), \dots, (a_r, a'_r, b_r)) = \begin{cases} (f_{\mathcal{B}}(a_{-r}, \dots, a_r), f_{\mathcal{B}^{-1}}(a'_{-r}, \dots, a'_r), \chi(a_0, b_0)) & \text{if } b_0 = 1, \\ (f_{\mathcal{B}^{-1}}(a_{-r}, \dots, a_r), f_{\mathcal{B}}(a'_{-r}, \dots, a'_r), \chi(a'_0, b_0)) & \text{if } b_0 = 0, \end{cases}$$

where  $\chi(a, b)$  equals  $1 - b$  if  $a \in F$  and  $b$  else. Intuitively, on configurations where the third component is uniform equal to  $b$ ,  $\mathcal{C}_0$  mimics  $\mathcal{B}$  on the first component and  $\mathcal{B}^{-1}$  on the second one if  $b = 1$  or the converse if  $b = 0$ . Moreover, the value of  $b$  is switched each time the component playing  $\mathcal{B}$  encounters a firing state. Hence, if we choose for  $\pi$  the projection on third component,  $\mathcal{C}_0$  started from configurations  $c_n$  has the property 'cycle' and produces the periodic sequence  $u_n$ .

We now enrich  $\mathcal{C}_0$  with a spreading state which is produced each time one of the following local checking fails:

- the third component  $\{0, 1\}$  must be uniform;
- for the two first components, a state from  $F$  (firing state) must always be surrounded by states from  $F$  only;
- states from  $F$  are forbidden on the second component if  $b = 1$  and states from  $F$  in the first component are forbidden if  $b = 0$ .

The third condition ensures that in the case of a 'cycle' regime (firing states appearing infinitely often), the period is equally divided between steps where  $b = 0$  and steps where  $b = 1$ . To ensure that such a 'cycle' regime always produces an alternance of exactly  $3n$  zeros and  $3n$  ones, we add a component implementing a counter modulo 3: the value of this component is incremented modulo 3 at each step (whatever the context) and a spreading state is generated if a cell contains a firing state and the counter is not 0 modulo 3. Denote by  $\mathcal{C}$  the CA obtained and consider any configuration  $c$ . If no spreading state appears in the orbit of  $c$ , then the third component is uniform. If it changes of state only a finite number of times, then we are in the 'frozen' regime. If there are infinitely many changes, it follows from the discussion above that the conditions of the 'cyclic' regime are fulfilled.

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<sup>7</sup>In [16], the main concern is synchronisation of finite segments of cells surrounded by a quiescent state. To extend the property to infinite configurations, it is crucial that "garbage" (which must be conserved to ensure reversibility) do not spread outside the initial segment. The solution of K. Imai and K. Morita has precisely this property as it is explicitly mentioned in [16].

To conclude the theorem, it remains to prove that  $\mathcal{C}$  is not  $\preceq_m$ -universal. Suppose for the sake of contradiction that it is and let  $\mathcal{U}$  be any universal CA without spreading state and consider the set  $X$  of configurations of  $\mathcal{C}$  which is the support of the strong simulation of  $\mathcal{U}$  ( $\mathcal{C}$  strongly simulates  $\mathcal{U}$  by theorem 5.1).  $X$  cannot contain any occurrence of the spreading state (by lemma 5.1), it implies that all configurations of  $X$  have a uniform third component. But, on such configuration, the dynamics of  $\mathcal{C}$  is reversible. Hence  $\mathcal{U}$  is reversible: this is a contradiction with its universality by theorem 4.3. ■

The synchronization layer of limit products is exactly the automaton  $\mathcal{C}$  of the previous theorem, except that the spreading state of  $\mathcal{C}$  now becomes a global spreading state. Before establishing the main result of this section, we give more details concerning the state layer and the transport layer of  $\mathcal{A}_\infty$ .

The state layer is made from state set  $S_{\mathcal{A}} \times \{L, C, R\}$  where  $L$ ,  $C$  and  $R$  are states to identify explicitly the role of each cell in each block  $B_{z,i}$ :  $C$  for the cell storing the  $i$ th component of cell  $z$  of  $\mathcal{A}$  and  $L$  and  $R$  to temporarily store states of  $i$ th component of cells  $z - 1$  and  $z + 1$  respectively.

The transport layer is made from state set  $S_{\mathcal{A}} \cup \{\perp\}$  where  $\perp$  is the state used to separate particle carrying a state from  $S_{\mathcal{A}}$ .

So the states set of  $\mathcal{A}_\infty$  is:

$$\underbrace{S_{\mathcal{A}} \times \{L, C, R\}}_{\text{state}} \times \underbrace{S_{\mathcal{A}} \cup \{\perp\}}_{\text{transport}} \times \underbrace{S_{\mathcal{C}} \setminus \{\kappa\}}_{\text{synchronization}} \cup \{\kappa\}.$$

In addition to the behavior described above,  $\mathcal{A}_\infty$  does the following local checkings and generates the spreading state  $\kappa$  if one of them fails:

- the second component of transport layer must be periodic of period  $LCR$ ;
- the transport layer must contain an alternance of one state from  $S_{\mathcal{A}}$  and two states  $\perp$ ;
- when doing read and write operations, the particles of the transport layer must be aligned with the right type of state in the state layer:
  - type  $C$  when reading,
  - type  $R$  when writing at step 2,
  - type  $L$  when writing at step 4;
- when the synchronisation layer says 'transition', check that the particles are aligned with cell of type  $C$  in the state layer.

All those checkings ensure the following property: if no spreading state is generated and if the component layer produces a correct cycle of instructions, then the behavior of the state layer is equivalent to the behavior of some Cartesian product of  $\mathcal{A}$  (up-to some rescaling).

Before stating the main theorem, we establish a simple yet useful lemma saying that if  $\mathcal{A}$  simulates  $\mathcal{B}$  with support  $X$ , then everything  $\mathcal{A}$  can simulate using a support included in  $X$  can also be simulated by  $\mathcal{B}$ .

**Lemma 6.1.** *Let  $\preceq$  be either  $\preceq_i$  or  $\preceq_m$ . Let  $\mathcal{A}$  and  $\mathcal{B}$  be such that the simulation  $\mathcal{A} \preceq \mathcal{B}$  occurs on a support  $X$  of configurations of  $\mathcal{B}$ . If  $\mathcal{B} \preceq$ -simulates  $\mathcal{C}$  on a support included in  $X$ , then  $\mathcal{A} \preceq$ -simulates  $\mathcal{C}$ .*

PROOF. We consider the case where  $\preccurlyeq$  is  $\preccurlyeq_i$ . By hypothesis, we have  $\mathcal{A}^{(\alpha)} \sqsubseteq_i \mathcal{B}^{(\beta_1)}$  on support  $X$  and  $\mathcal{C}^{(\gamma)} \sqsubseteq_j \mathcal{B}^{(\beta_2)}$  on support  $Y \subseteq X$ . Now, let  $m_\alpha, m_{\beta_1}, m_{\beta_2}$  and  $m_\gamma$  be the packing parameters of transforms  $\alpha, \beta_1, \beta_2$  and  $\gamma$  respectively. The injective maps  $i$  and  $j$  induce two injective maps  $i_{\beta_2}$  and  $j_{\beta_1}$  with the following domains and ranges:

$$\begin{aligned} i_{\beta_2} : S_{\mathcal{A}}^{m_\alpha m_{\beta_2}} &\rightarrow S_{\mathcal{B}}^{m_{\beta_1} m_{\beta_2}} \\ j_{\beta_1} : S_{\mathcal{C}}^{m_\gamma m_{\beta_1}} &\rightarrow S_{\mathcal{B}}^{m_{\beta_1} m_{\beta_2}} \end{aligned}$$

Therefore  $\phi = i_{\beta_2}^{-1} \circ j_{\beta_1}$  is a well-defined injective map from  $S_{\mathcal{C}}^{m_\gamma m_{\beta_1}}$  into  $S_{\mathcal{A}}^{m_\alpha m_{\beta_2}}$ . Now define the transforms  $\eta_a$  and  $\eta_c$  to be the composition of  $\alpha$  and  $\beta_2$ , and of  $\gamma$  and  $\beta_1$  respectively. Then we have  $\mathcal{C}^{(\eta_c)} \sqsubseteq_\phi \mathcal{A}^{(\eta_a)}$ .

The extension of the previous reasoning to  $\preccurlyeq_m$  is straightforward.  $\blacksquare$

This lemma together with lemma 5.1 is the key to a kind of 'self-checking' simulation used in the construction of the limit product (and re-used in section 6.2). A 'self-checking' simulation of  $\mathcal{B}$  by  $\mathcal{A}$  is standard simulation of  $\mathcal{B}$  by  $\mathcal{A}$  on some support  $X$  with the additional property that  $\mathcal{A}$  'checks' locally on any configuration that it belongs to  $X$ , and triggers some pathological behavior (typically a spreading state) in case of check failure. Hence any possible strong simulation of some  $\mathcal{C}$  by  $\mathcal{A}$  is such that:

- either it has a support included in  $X$  in which case  $\mathcal{B}$  can also simulate  $\mathcal{C}$  by lemma 6.1,
- or it must contain some  $c \notin X$  in its support in which case a spreading state is generated and lemma 5.1 gives some limitation on  $\mathcal{C}$ .

To show that a spreading state is generated in the second case above, a crucial property is that the support of any simulation is by definition always irreducible: if  $u_1$  and  $u_2$  are words occurring in two configurations of the support, there exists a third configuration of the support where  $u_1$  and  $u_2$  both appear (see section 3.2 of [8] for a more detailed discussion on supports of simulations).

We now state the main theorem of this section.

**Theorem 6.3.** *For any  $\mathcal{A}$ , its limit product  $\mathcal{A}_\infty$  is such that:*

- $\underbrace{\mathcal{A} \times \cdots \times \mathcal{A}}_n \preccurlyeq_m \mathcal{A}_\infty$  for all  $n \geq 1$ ,
- $\mathcal{A}_\infty$  is  $\preccurlyeq_m$ -universal if and only if  $\mathcal{A}$  is  $\preccurlyeq_m$ -universal.

PROOF. The first assertion follows from the construction of  $\mathcal{A}_\infty$  and the detailed discussion above. Now suppose that  $\mathcal{A}_\infty$  is  $\preccurlyeq_m$ -universal and let  $\mathcal{U}$  be any universal CA with no spreading state. By theorem 5.1,  $\mathcal{A}_\infty$  strongly simulates  $\mathcal{U}$ :  $\mathcal{U} \sqsubseteq \mathcal{A}_\infty^{(\alpha)}$  for some geometrical transform  $\alpha$ . Let  $X$  denote the support of the simulation. By choice of  $\mathcal{U}$ , the spreading state  $\kappa$  cannot appear in any orbit of any configuration of  $X$  (by lemma 5.1). We deduce from theorem 6.2 that the synchronization component is in the same regime (either 'cycle' for a fixed value  $n$  or 'frozen') for all the configurations of  $X$  because otherwise, we could construct a configuration in  $X$  producing a spreading state (by irreducibility of  $X$ ).



In the case where all configurations are in the frozen regime, the flag of the synchronization layer becomes constant after some time  $t_0$ , so the transport layer has the behavior of a translation (or identity) and the state layer remains constant.  $t_0$  is identical for all configurations of  $X$  (because otherwise, we could once more combine two configurations to produce a spreading state, by irreducibility of  $X$ ). Then, consider a CA  $\mathcal{U}_+$  with state set  $S_{\mathcal{U}} \times \{0, \dots, t_0\}$  which has the following behavior:

- the second component is decreased by one until it reaches 0;
- on the first component, the local rule of  $\mathcal{U}$  is applied, but only if the second component is 0.

Since  $\mathcal{U}$  is  $\preceq_m$ -universal, it can strongly simulate  $\mathcal{U}_+$  (by theorem 5.1): precisely,  $\mathcal{U}_+ \preceq \mathcal{U}^{(m,1,t,z)}$ . Consider the set  $Y$  of configurations of  $\mathcal{U}$  corresponding via simulation to the set of configurations of  $\mathcal{U}_+$  uniformly equal to  $t_0$  on the second component. Denote by  $X_Y \subseteq X$  the corresponding set of configurations of  $\mathcal{A}_\infty$ . By choice of  $\mathcal{U}_+$ , we know that  $\mathcal{U}$  simulates itself on the set of configurations  $G_{\mathcal{U}}^{tt_0}(Y)$ . This implies that for some  $t' \geq t_0$ ,  $\mathcal{A}_\infty$  can simulate  $\mathcal{U}$  using as support the set of configurations  $G_{\mathcal{A}_\infty}^{t'}(X_Y)$ . By hypothesis, starting from such configurations,  $\mathcal{A}_\infty$  has a behavior of translation or identity on the state and transport layers. Since the synchronizing component evolves independently of the others, we deduce by lemma 6.1 that there is some CA  $\mathcal{B}$  which is a product of translations (corresponding to state and transport layers) such that  $\mathcal{B} \times \mathcal{C}$  simulates  $\mathcal{U}$ : this is a contradiction by theorem 5.4 since neither  $\mathcal{B}$  (theorem 3.4), nor  $\mathcal{C}$  (theorem 6.2) is universal.

Hence, we are necessarily in the case where the synchronization layers produce a valid cycle. Since no spreading state can be generated in the orbit of any configuration of  $X$ , the state layer always behaves like a Cartesian product of  $n$  copies of  $\mathcal{A}$ . The value of  $n$  is in fact common to all configurations of  $X$  (as shown above), so we deduce by lemma 6.1 that  $\underbrace{\mathcal{A} \times \dots \times \mathcal{A}}_n$  simulates  $\mathcal{U}$  and  $\mathcal{A}$

is therefore universal by theorem 5.4. ■

Of course, we can consider  $\mathcal{A}_\infty$  itself as a new candidate for taking its finite Cartesian products and applying the limit product construction. In fact, the process can be repeated forever with the guarantee that no CA ever produced in this chain will be universal, provided the initial CA is not. However, there is no reason why this infinite chain should be strictly increasing. In particular, even if

$$\mathcal{A} \preceq \mathcal{A} \times \mathcal{A} \preceq \mathcal{A} \times \mathcal{A} \times \mathcal{A} \preceq \dots$$

is a strictly increasing chain, it might be the case that  $\mathcal{A}_\infty$  is equivalent to  $\mathcal{A}_\infty \times \mathcal{A}_\infty$ . Therefore we have only proven that one of the following properties is true:

- there is a strictly increasing chain of length  $\omega \times \omega$  in the quasi-order  $(AC, \preceq_m)$ ,
- for any non-universal CA  $\mathcal{A}$ , there is a non-universal CA  $\mathcal{B}$  such that  $\mathcal{A} \preceq_m \mathcal{B}$  and  $\mathcal{B} \times \mathcal{B}$  is equivalent to  $\mathcal{B}$ .

## 6.2. Sub-Families of Cellular Automata

Theorem 2.3 shows that any equivalence class in any quasi-order contains some CA with radius 1. This fact is a direct consequence of a well-known transformation of CA with large radius into CA of smaller radius with more states (this transformation is called 'higher block presentation' in symbolic dynamics, see [21]).

It is also sometimes invoked in the literature that considering CA with two states only is not restrictive since there is a converse transformation that transforms a CA with many states into a CA with only two states but a larger radius. However, the situation is not similar to that of radius reduction since there are equivalence classes with no 2-states CA: *e.g.*  $\mathcal{Z}_p$  for any prime  $p \neq 2$  as shown by theorem 3.2 and lemma 3.2. Note that the same is true for any fixed state set of cardinal  $n$ : the equivalence class of  $\mathcal{Z}_p$  contains no such CA provided  $p$  is prime and does not divide  $n$ .

Hence, this transformation introduces a bias: the transformed CA may be inequivalent to the original one. Meanwhile, we know that CA with two states can be as powerful as CA in general since there are universal CA with two states only [2, 28] (for simulation relations  $\preceq_i$  and  $\preceq_m$ ). More precisely, as we will see below, the transformation applied to a universal CA always yields a universal CA because the transformed CA simulates the original one. Since the original and the transformed CA are not always in the same equivalence class, one question that naturally arises is: what CA can be simulated by the transformed CA but not by the original one? Although it provides only partial answers, this section is devoted to that kind of questions, for CA with two states and for other families.

Formally, given a family  $\mathfrak{F}$  of CA, we say that a map  $\phi : AC \rightarrow \mathfrak{F}$  is a  $\preceq$ -encoding of CA into family  $\mathfrak{F}$  if

$$\forall \mathcal{A}, \mathcal{A} \preceq \phi(\mathcal{A}).$$

We will only consider simulation relations  $\preceq_i$  and  $\preceq_m$  in the sequel, thus an encoding into  $\mathfrak{F}$  implies that there are universal CA in  $\mathfrak{F}$ . A trivial example of such an encoding is given by  $\mathfrak{F} = \{\mathcal{U}\}$  where  $\mathcal{U}$  is a universal CA and  $\phi$  is the function mapping any CA to  $\mathcal{U}$ . We are interested in using this notion of encoding with families which are more 'representative' of the diversity of behaviors in the whole set of CA. To express this we introduce the following notion of *faithfulness*.

Given a  $\preceq$ -encoding  $\phi : AC \rightarrow \mathfrak{F}$  and a set  $E$  of CA, we say that  $\phi$  is *faithful* for  $E$  if:

$$\forall \mathcal{B} \in E : \mathcal{B} \preceq \mathcal{A} \iff \mathcal{B} \preceq \phi(\mathcal{A}).$$

An encoding is faithful for  $E$  if the original CA and its image by the encoding simulate exactly the same CA in  $E$ . So, to give some evidence that a family  $\mathfrak{F}$  is 'representative' of CA in general, we can exhibit an encoding of CA into  $\mathfrak{F}$  which is faithful for a set  $E$  of CA as large as possible. When  $E$  is the whole set of CA, the faithfulness implies that there is a CA of family  $\mathfrak{F}$  in any equivalence class: this is the case for CA with radius 1.

The next theorem gives four encodings which are faithful for  $U$ , the set of  $\preceq_m$ -universal CA. The families corresponding to these encodings were already defined in this paper except one: captive CA.

Captive CA were introduced in [35] and are defined by a simple restriction on the transition rule. A CA  $\mathcal{A}$ , with state set  $S_{\mathcal{A}}$ , radius  $r$  and local rule  $f_{\mathcal{A}}$  is captive if:

$$\forall a_{-r}, \dots, a_r \in S_{\mathcal{A}} : f_{\mathcal{A}}(a_{-r}, \dots, a_r) \in \{a_{-r}, \dots, a_r\}.$$

In the following theorem, encodings are different but their faithfulness rely on the same idea of 'self-checking' simulation explained above which uses lemma 5.1 and lemma 6.1.

**Theorem 6.4.** *Let  $\preceq$  be  $\preceq_i$  or  $\preceq_m$ . For any family of CA below, there is a  $\preceq$ -encoding from CA into  $\mathfrak{F}$  which is faithful for the set  $U$  of  $\preceq_m$ -universal CA:*

- CA with two states,
- CA in  $\mathcal{T}_2$ ,
- CA in  $\mathcal{T}_3$ ,
- captive CA.

PROOF. To describe the encoding for each family, we suppose  $\mathcal{A}$  is a CA with state set  $S_{\mathcal{A}} = \{a_1, \dots, a_n\}$ , with radius  $r$  and location rule  $f_{\mathcal{A}}$ .

**2-states CA.** Let  $m$  be an integer large enough and  $\psi$  be an injective map from  $S_{\mathcal{A}}$  to  $\{0, 1\}^m$  such that no word  $\psi(a)$  contains an occurrence of 11. Now define the injective map  $i : S_{\mathcal{A}} \rightarrow \{0, 1\}^{m+4}$  by  $i(a) = 0110\psi(a)$ . Let  $r' = (r + 1)(m + 4)$ .  $\phi(\mathcal{A})$  is a CA of radius  $r'$  and state set  $\{0, 1\}$  defined as follows:

- on the set  $X$  of configurations made of infinite concatenations of words from  $i(S_{\mathcal{A}})$ ,  $\phi(\mathcal{A})$  is isomorphic to  $\mathcal{A}$  so that  $\mathcal{A} \sqsubseteq_i \phi(\mathcal{A})$ ;
- everywhere else,  $\phi(\mathcal{A})$  generates a 1.

The map  $\phi$  is thus an encoding of CA into 2-states CA. Now suppose that  $\phi(\mathcal{A})$  is universal and let  $\mathcal{U}$  be a universal CA with two states and no spreading state which is strongly simulated by  $\phi(\mathcal{A})$  on support  $Y$  (theorem 5.1). If there is some  $y \in Y$  with  $y \notin X$  then

- either there are two occurrences of 0110 in  $y$  which are not correctly spaced,
- or there is a word 0110 $u$ 0110 occurring in  $y$  with  $u \notin \psi(S_{\mathcal{A}})$ .

In any case, the image of  $y$  will contain an occurrence of 111 (because the above error must be seen by at least three consecutive cells) and 1's will propagate like a spreading state which is impossible by lemma 5.1 because otherwise  $\phi(\mathcal{A})^{(3,1,1,0)}$  could simulate  $\mathcal{U}$  on a support where it possesses the spreading state 111. So  $Y \subseteq X$  and lemma 6.1 shows that  $\mathcal{A}$  simulates  $\mathcal{U}$ . Hence  $\mathcal{A}$  is universal if and only if  $\phi(\mathcal{A})$  is.

**Captive CA.** The encoding technique for captive CA is very similar and already appeared in a non-faithful form in [35]. Let  $u$  be the word  $a_1 \dots a_n$ , let  $\#$  be a state not in  $S_{\mathcal{A}}$  and denote  $Q = S_{\mathcal{A}} \cup \{\#\}$ . We define the injective map  $i : S_{\mathcal{A}} \rightarrow Q^{n+3}$  by  $i(a) = \#u\#a$ . We then define  $\phi(\mathcal{A})$  in a way similar to the case above. Its radius is  $r' = (r + 1)(n + 3)$ , its state set is  $Q$  and its local rule is such that:

- on the set  $X$  of configurations made of infinite concatenations of words from  $i(S_{\mathcal{A}})$ ,  $\phi(\mathcal{A})$  is isomorphic to  $\mathcal{A}$  so that  $\mathcal{A} \sqsubseteq_i \phi(\mathcal{A})$ ;
- everywhere else,  $\phi(\mathcal{A})$  take as new state the maximum of its neighbors for some fixed ordering of  $Q$  such that  $\#$  is the maximum.

First,  $\phi(\mathcal{A})$  is captive and  $\phi$  defines an encoding of CA into captive CA. Second, notice that for any support of simulation  $Y$  of  $\phi(\mathcal{A})$ , if there is some  $y \in Y$  with  $y \notin X$  then, by irreducibility of  $Y$ , either there is  $y' \in Y$  with  $y' \notin X$  and  $y'$  contains a  $\#$ , or  $\#$  never appears in  $Y$ . In the second case,  $\phi(\mathcal{A})$  always applies a max as local rule and therefore possesses a spreading state when restricted to  $Y$ . In the first case, consider the configuration  $y'$  and  $z \in \mathbb{Z}$  such that positions  $z$  and  $z + 1$  both see a  $\#$  in their neighborhood and a local pattern not in  $X$  (such a  $z$  must exist by choice of  $y'$  and definition of  $X$ ). Then  $\phi(\mathcal{A})(y')$  contains the pattern  $\#\#$  which is spreading by definition of  $\phi(\mathcal{A})$ . In any case we can apply the usual reasoning with lemma 5.1 and lemma 6.1: any CA without spreading state strongly simulated by  $\phi(\mathcal{A})$  is also simulated by  $\mathcal{A}$ . So the encoding  $\phi$  is faithful for universal CA.

$\mathcal{T}_2$  and  $\mathcal{T}_3$ . For  $\mathcal{T}_2$ , the encoding is simple:  $\phi(\mathcal{A})$  is just  $\mathcal{A}$  with an additional state  $\kappa$  which is spreading. The resulting CA  $\phi(\mathcal{A})$  is always in  $\mathcal{T}_2$  since  $\kappa^{2r}$  is a blocking word (see [19]). Lemma 5.1 is then sufficient to prove that it is an encoding from AC to  $\mathcal{T}_3$  which is faithful for universal CA.

For  $\mathcal{T}_3$ , the proof is even simpler:  $\phi(\mathcal{A}) = \mathcal{A} \times \sigma_1 \times \sigma_{-1}$  is always in  $\mathcal{T}_3$  since  $\sigma_1 \times \sigma_{-1} \in \mathcal{T}_3$  and an equicontinuous point in a Cartesian product induce equicontinuous points for each component. Theorem 5.4 concludes for the faithfulness. ■

These encodings allow to transport some properties of general CA concerning the top of quasi-orders into order structures induced by each family<sup>8</sup>.

**Corollary 6.1.** *Let  $\preceq$  be  $\preceq_i$  or  $\preceq_m$  and let  $\mathfrak{F}$  be a family of CA among: CA with two states,  $\mathcal{T}_2$ ,  $\mathcal{T}_3$ , captive CA. Then we have the following properties:*

- the set of  $\preceq$ -universal CA in  $\mathfrak{F}$  is not co-r.e.
- for any non-universal  $\mathcal{A} \in \mathfrak{F}$ , there is a non universal  $\mathcal{B} \in \mathfrak{F}$  with  $\mathcal{A} \preceq \mathcal{B}$  but  $\mathcal{B} \not\preceq \mathcal{A}$ .

PROOF. The first property is a direct corollary of theorem 6.4 and 5.3 by definition of faithful encodings.

For the second property, consider the encoding  $\phi$  established in theorem 6.4 and let  $\mathcal{A} \in \mathfrak{F}$  be any non-universal CA. By theorem 5.4, there is some non-universal CA  $\mathcal{B}$  such that  $\mathcal{A} \preceq \mathcal{B}$  but  $\mathcal{B} \not\preceq \mathcal{A}$ . By faithfulness of  $\phi$ ,  $\phi(\mathcal{B}) \in \mathfrak{F}$  is not universal and by the definition of encoding it simulates  $\mathcal{A}$  without being simulated by  $\mathcal{A}$ . ■

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<sup>8</sup>A stronger result concerning captive CA appears in [37]:  $\preceq_i$ -universality is undecidable even if we restrict to captive CA with a fixed (but sufficiently large) radius.

The families considered above induce structures sharing some properties with the general quasi-orders 'near the top'. However, the complete characterisation of equivalence classes occupied by some CA of these families is more challenging.

**Open Problem 9.** *What are the equivalence classes of the simulation quasi-orders containing a 2-states CA? a captive CA? a CA from  $\mathcal{T}_2$ ? a CA from  $\mathcal{T}_3$ ?*

## 7. Summary of results

Figures 3, 5 and 4 hereafter give a summary of results and open problems concerning each of the three quasi-orders studied in the paper.

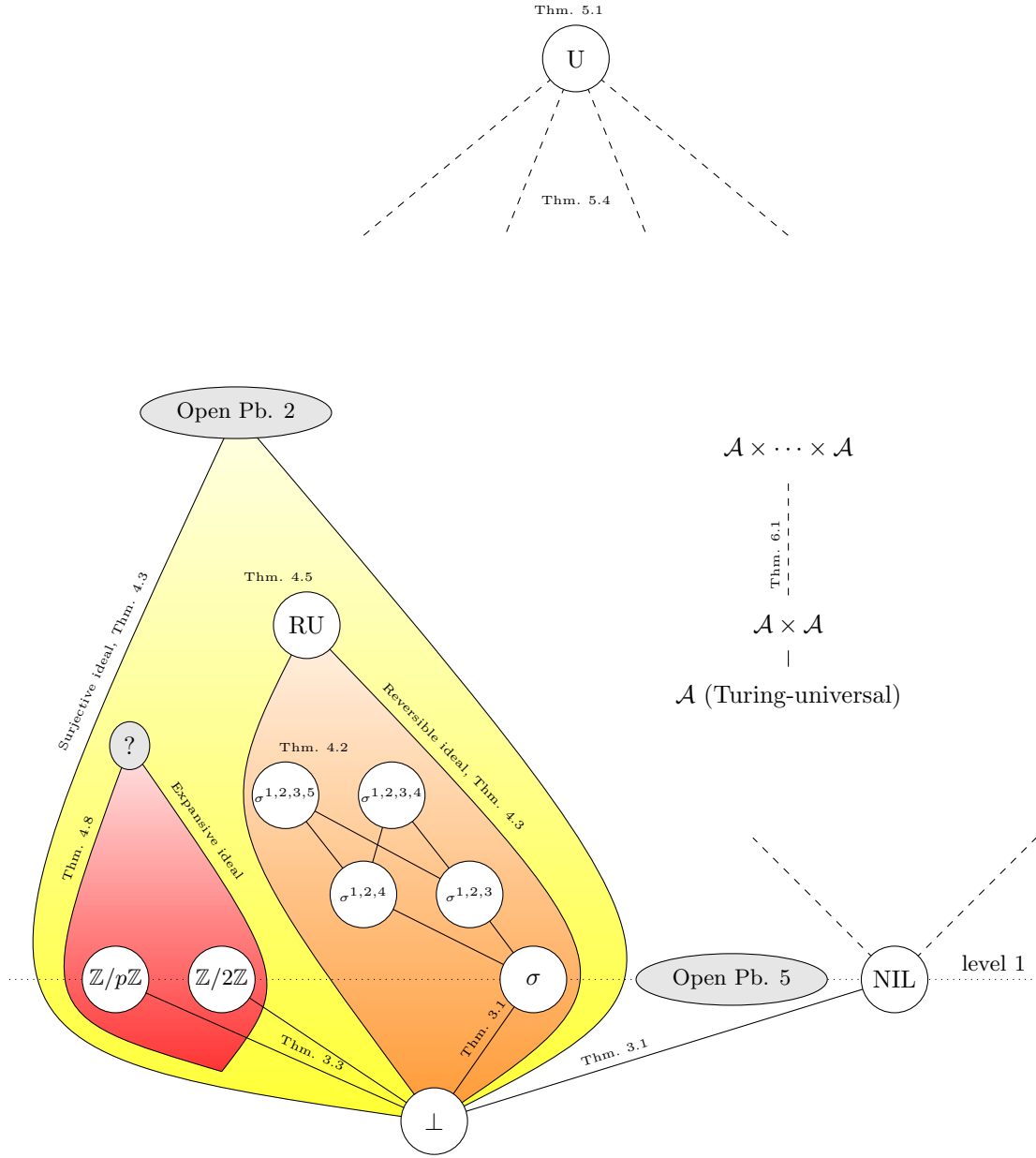
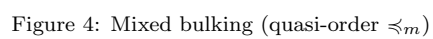


Figure 3: Injective bulking (quasi-order  $\preceq_i$ )



Open Pb. 7

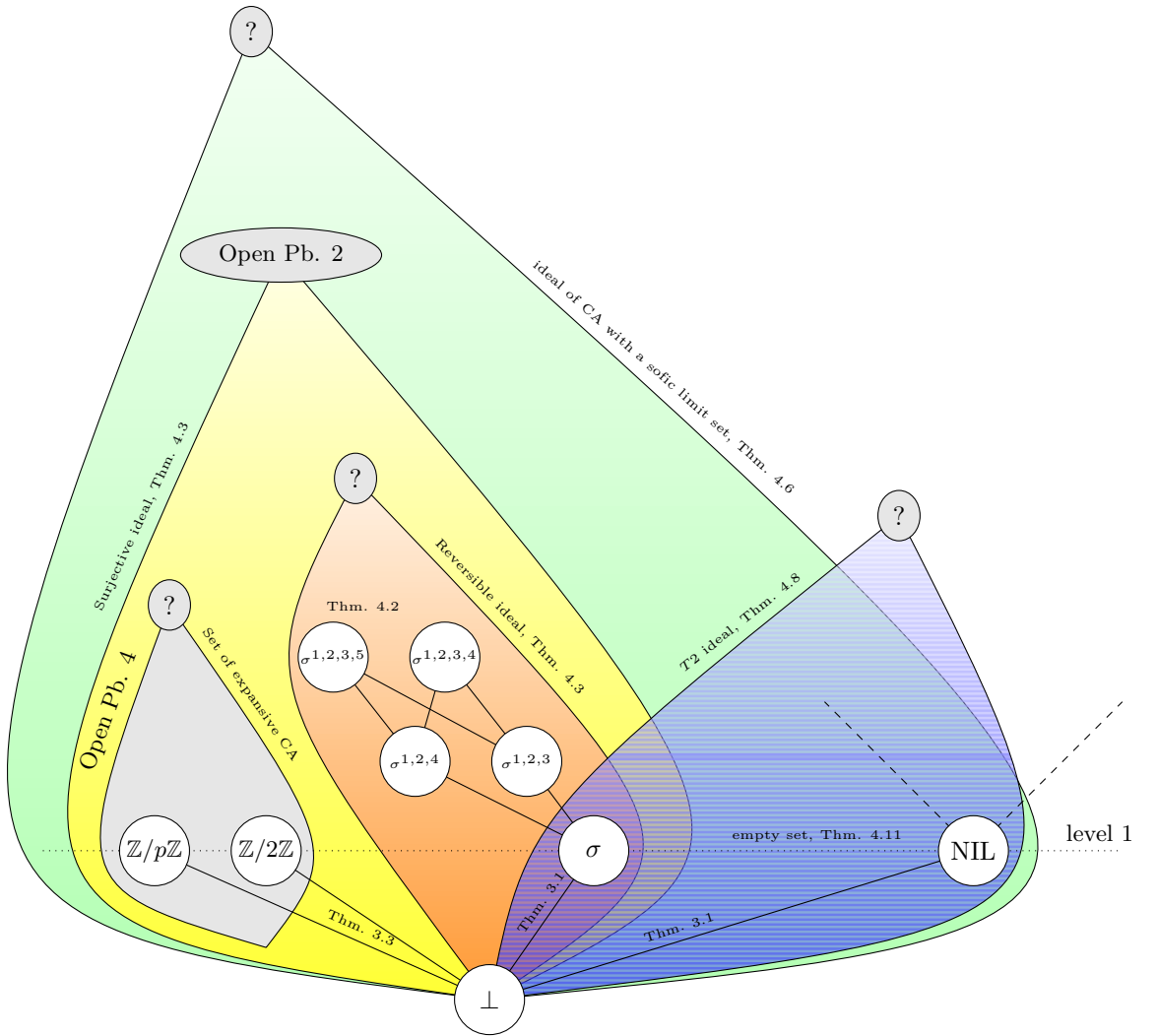


Figure 5: Surjective bulking (quasi-order  $\preceq_s$ )



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